THESEUS

TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR

Lorenzo Amati

(INAF – OAS Bologna)

on behalf of the THESEUS international collaboration

http://www.isdc.unige.ch/theseus/

Amati et al. 2018 (Adv.Sp.Res., arXiv:1710.04638)

Stratta et al. 2018 (Adv.Sp.Res., arXiv:1712.08153)

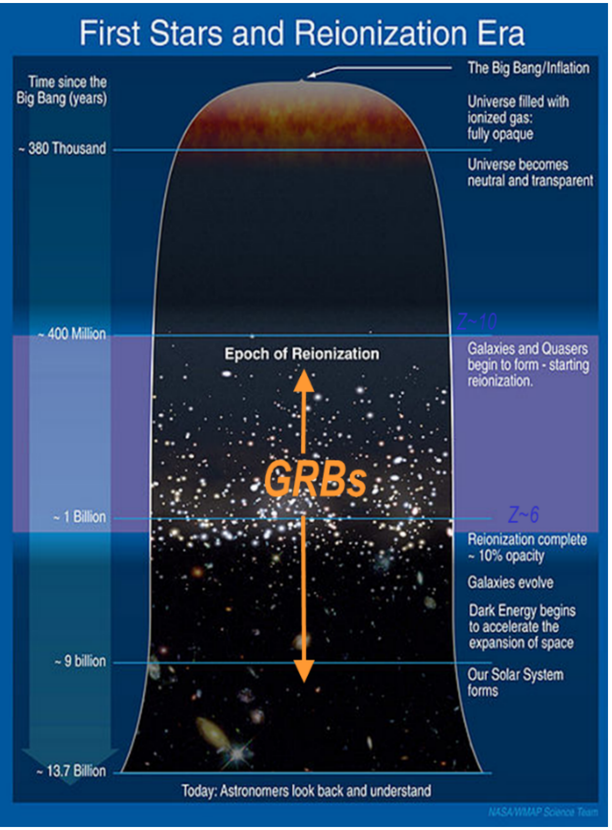
X-RAY ASTRONOMY 2019

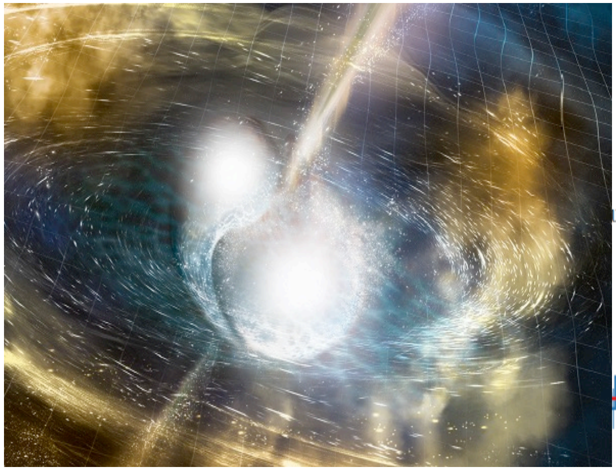
Current Challenges and New Frontiers in the Next Decade

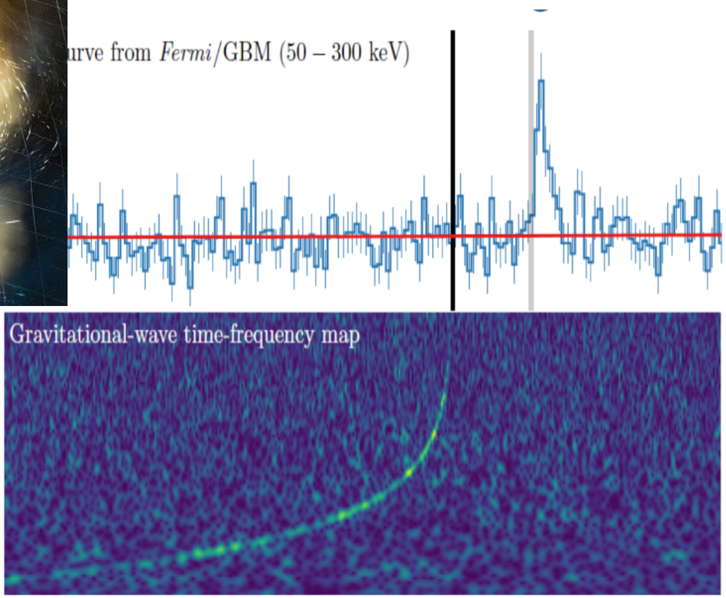
8-13 September 2019

CNR/INAF Research Area, Bologna, Italy

Probing the Early Universe with GRBs
Multi-messenger and time domain Astrophysics
The transient high energy sky
Synergy with next generation large facilities (E-ELT, SKA, CTA, ATHENA, GW and neutrino detectors)







THESEUS
Transient High Energy Sky and Early Universe Surveyor

Lead Proposer (ESA/M5): Lorenzo Amati (INAF – OAS Bologna, Italy)

Coordinators (ESA/M5): Lorenzo Amati, Paul O'Brien (Univ. Leicester, UK), Diego Gotz (CEA-Paris, France), C. Tenzer (Univ. Tuebingen, D), E. Bozzo (Univ. Genève, CH)

Payload consortium: Italy, UK, France, Germany, Switzerland, Spain, Poland, Czech Republic, Ireland, Hungary, Slovenia , ESA

Interested international partners: USA, China, Brazil

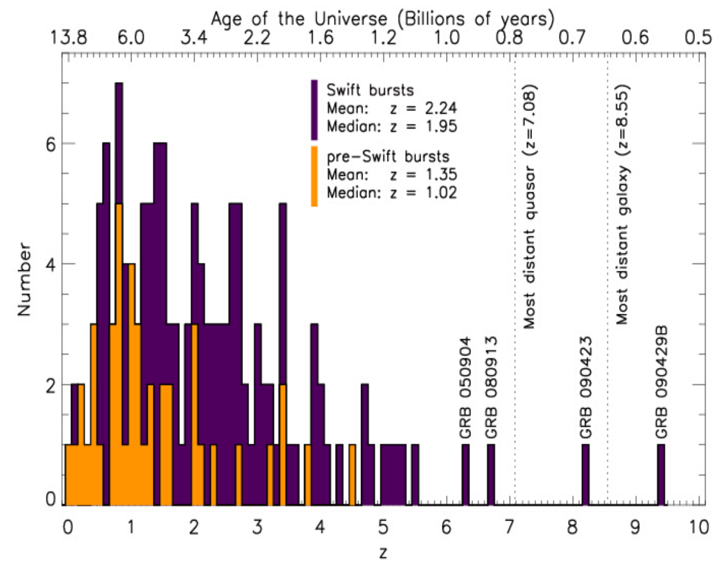
May 2018: THESEUS selected by ESA for M5 Phase 0/A study

Activity	Date
Phase 0 kick-off	June 2018
Phase 0 completed (EnVision, SPICA and THESEUS)	End 2018
ITT for Phase A industrial studies	February 2019
Phase A industrial kick-off	June 2019
Mission Selection Review (technical and programmatic review for the three mission candidates)	Comleted by May 2021
SPC selection of M5 mission	**June 2021**
Phase B1 kick-off for the selected M5 mission	December 2021
Mission Adoption Review (for the selected M5 mission)	March 2024
SPC adoption of M5 mission	June 2024
Phase B2/C/D kick-off	Q1 2025
Launch	2032

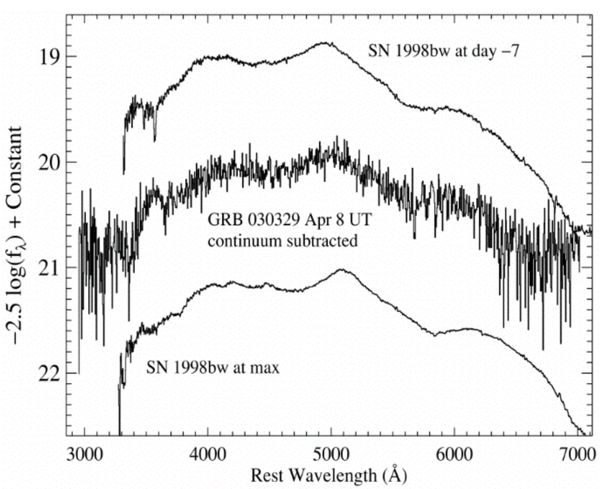
- ❑ **Smooth CDF study, successful MDR -> Phase A**
- ❑ Efficient and positive interaction between ESA and consortium

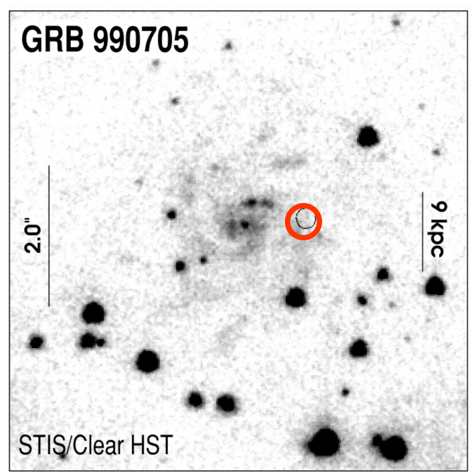
Shedding light on the early Universe with GRBs

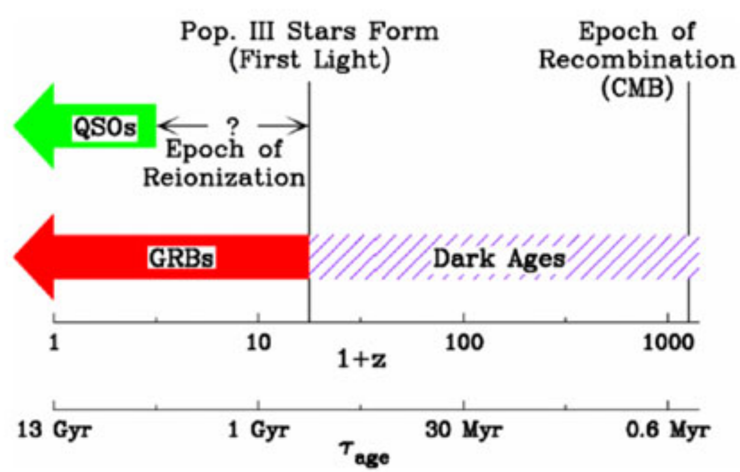
Because of their huge luminosities, mostly emitted in the X and gamma-rays, their redshift distribution extending at least to z ~9 and their association with explosive death of massive stars and star forming regions, GRBs are unique and powerful tools for investigating the early Universe: **SFR evolution, physics of re-ionization, galaxies metallicity evolution and luminosity function, first generation (pop III) stars**



GRBs in Cosmological Context





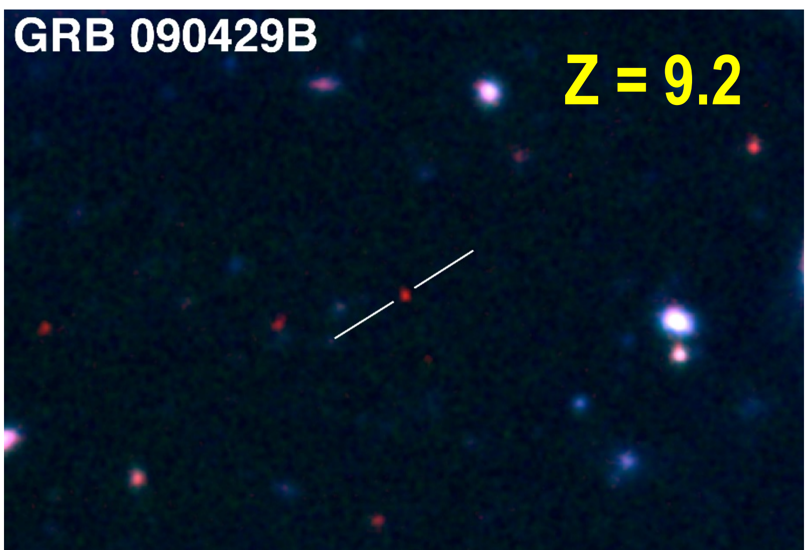


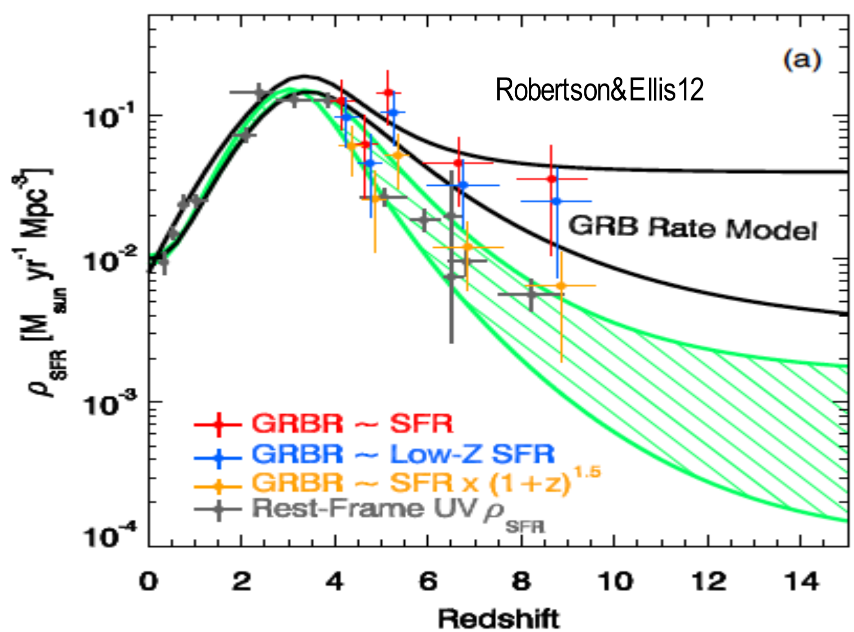
Lamb and Reichart (2000)

A statistical sample of high–z GRBs can provide fundamental information:

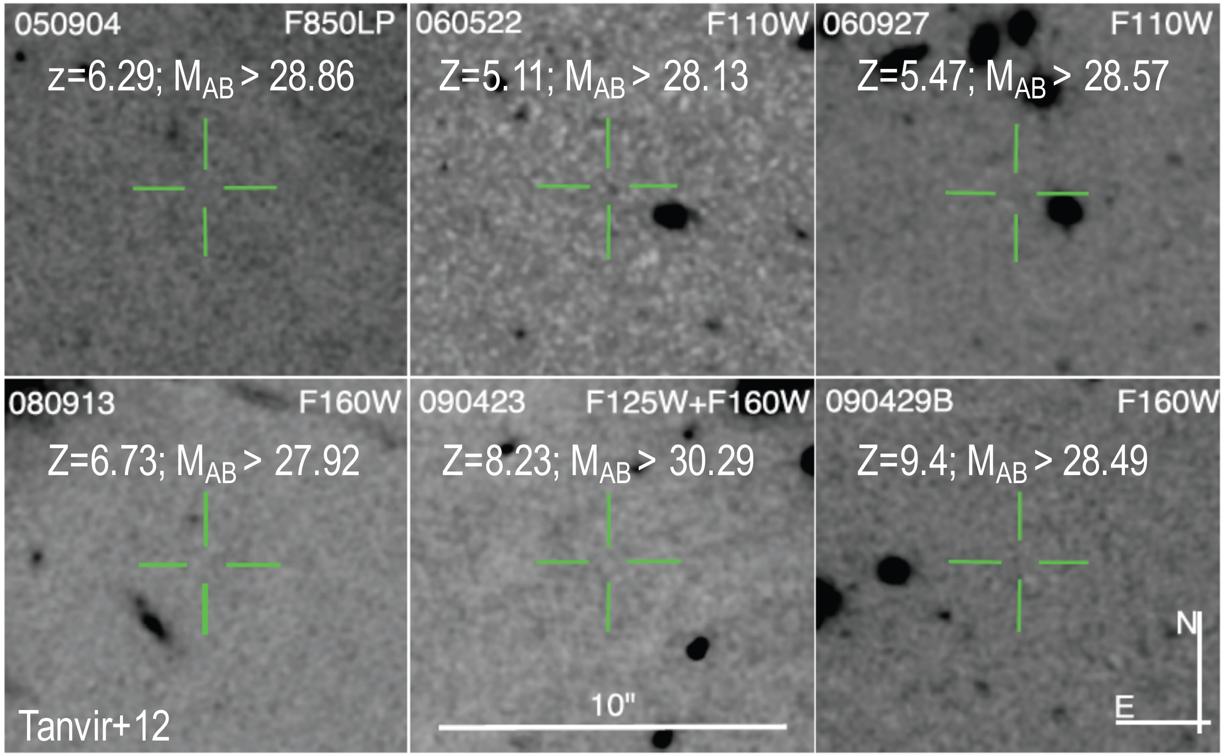
- measure independently the **cosmic star–formation rate**, even beyond the limits of current and future galaxy surveys

- directly (or indirectly) detect the **first population of stars (pop III)**





- the number density and properties of **low-mass galaxies**

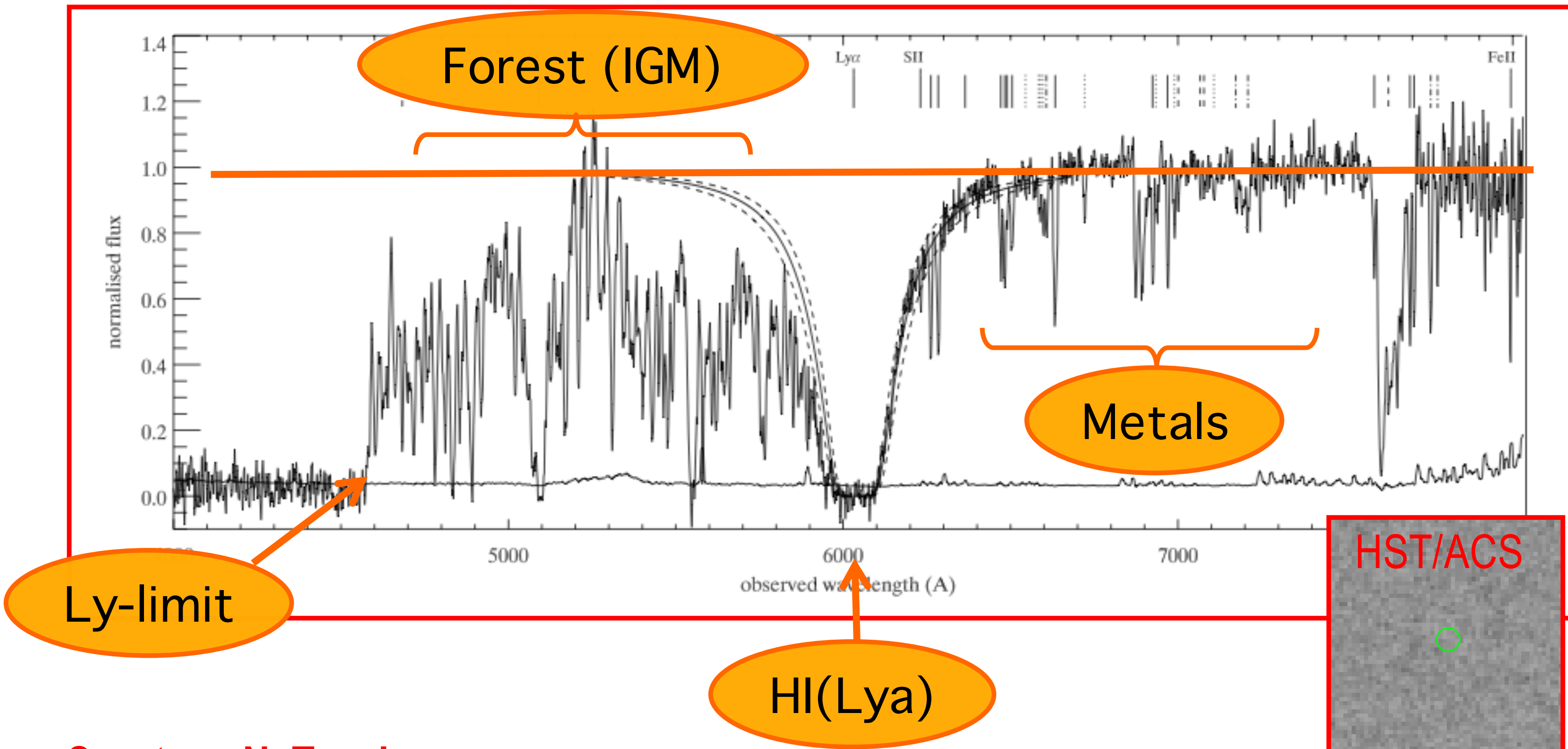


Robertson&Ellis12

Even JWST and ELTs surveys will be not able to probe the faint end of the galaxy Luminosity Function at high redshifts (z>6-8)

- **the neutral hydrogen fraction**
- **the escape fraction of UV photons from high-z galaxies**
- **the early metallicity of the ISM and IGM and its evolution**

Abundances, HI, dust, dynamics etc. even for very faint hosts. E.g. GRB 050730: faint host (R>28.5), but z=3.97, [Fe/H]=-2 and low dust, from afterglow spectrum (Chen et al. 2005; Starling et al. 2005).



Courtesy N. Tanvir

- the neutral hydrogen fraction
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Abu 050730:
faint spectrum
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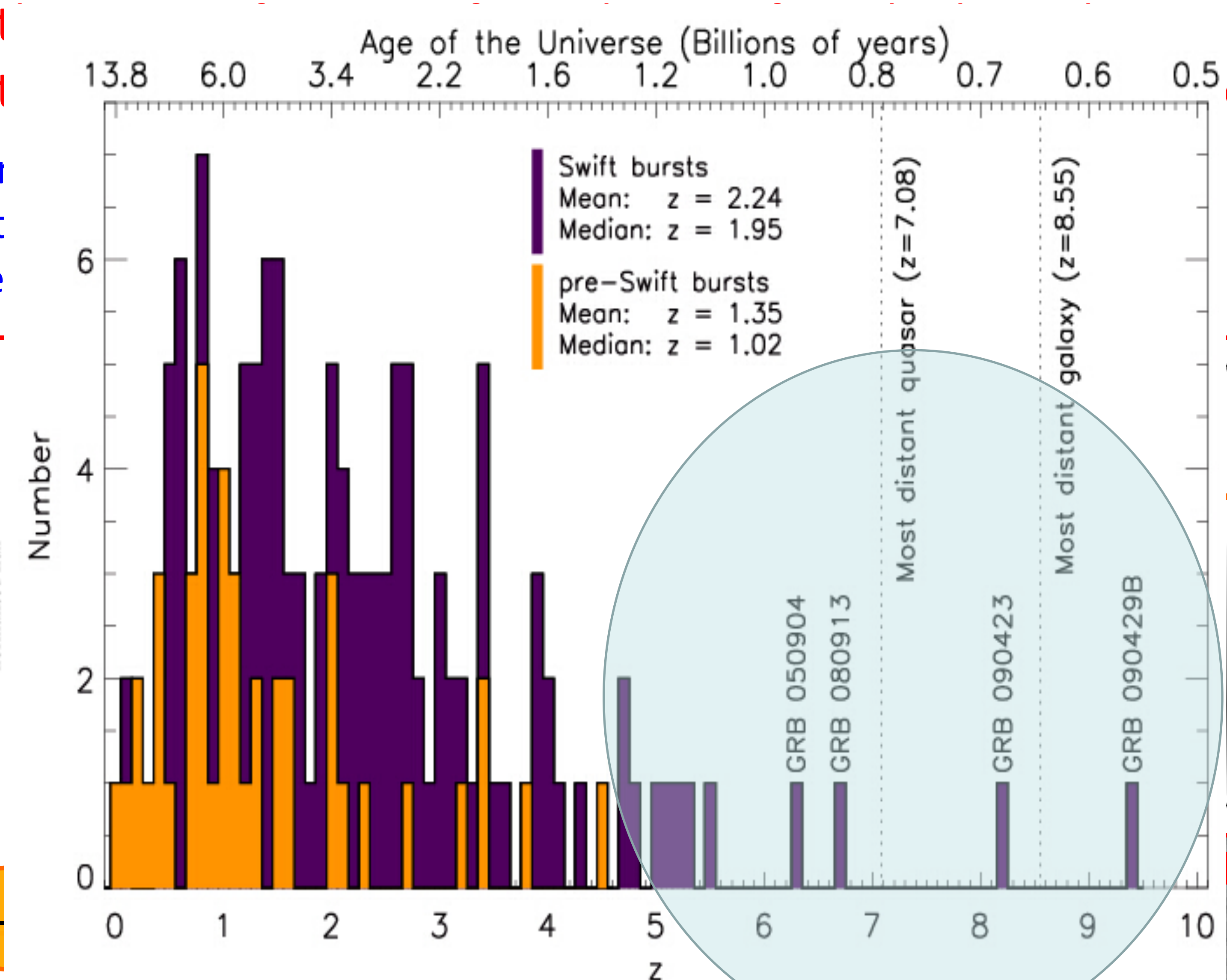

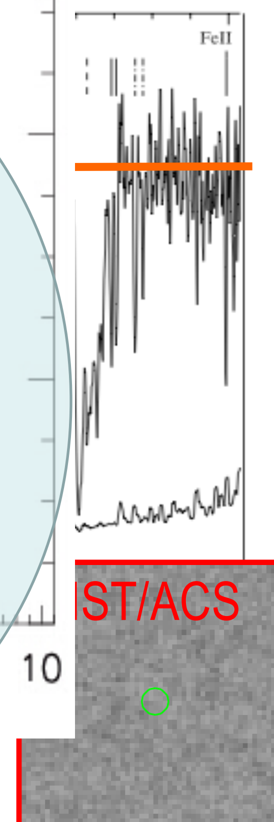

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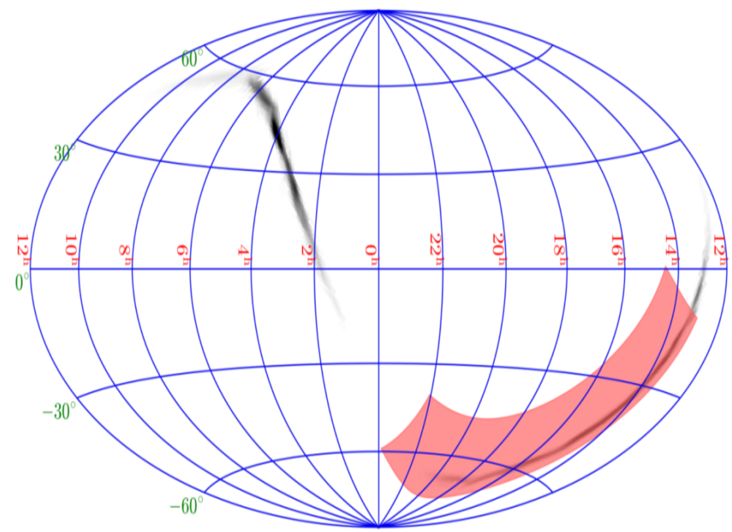
HI(Lya)

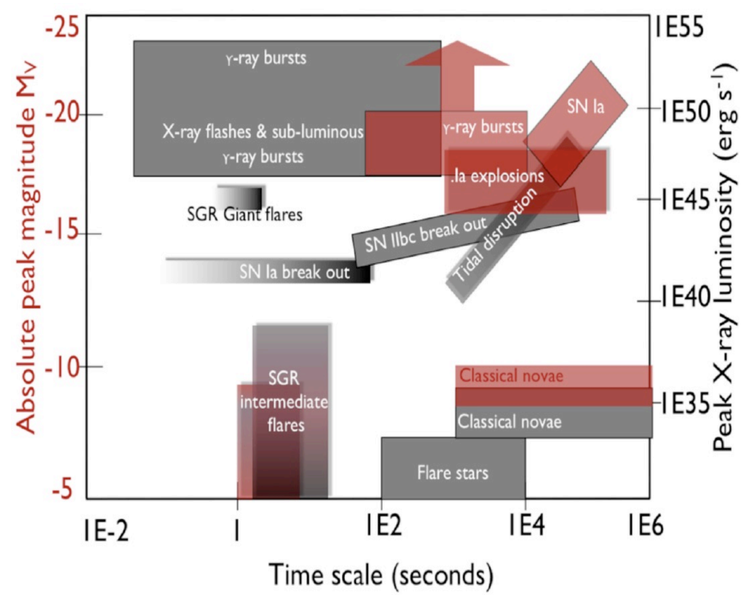
Courtesy N. Tanvir

Exploring the multi-messenger transient sky

- **Locate and identify the electromagnetic counterparts to sources of gravitational radiation and neutrinos, which may be routinely detected in the late '20s / early '30s by next generation facilities like aLIGO/aVirgo, eLISA, ET, or Km3NET;**

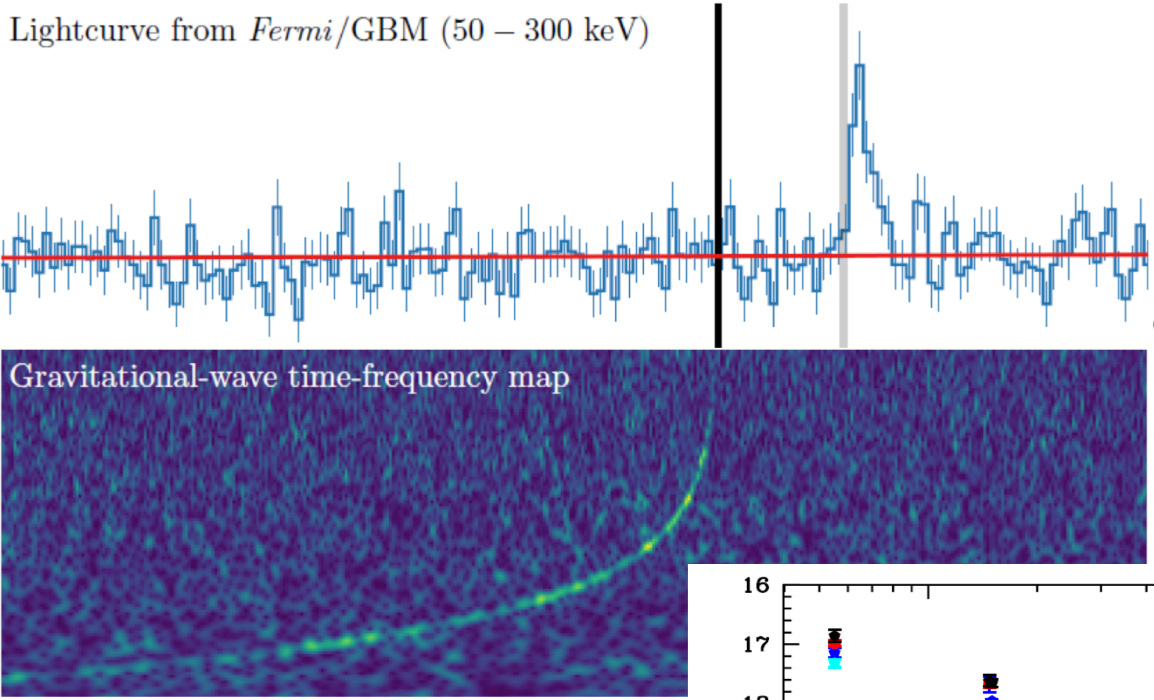


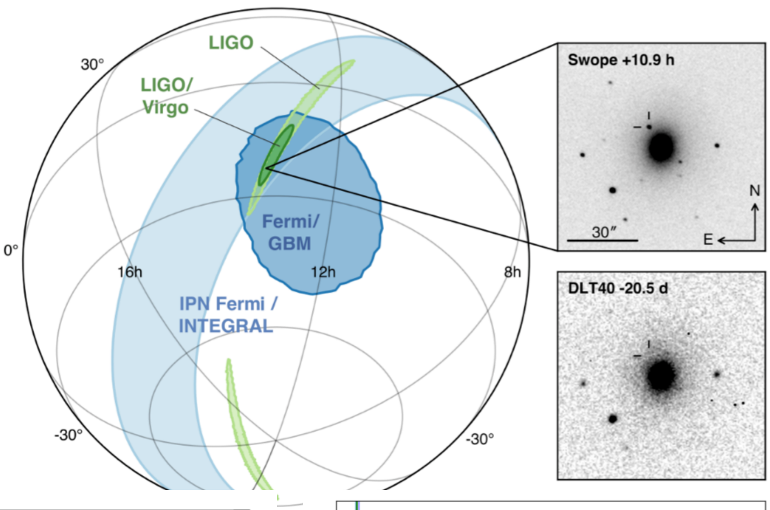
- Provide real-time triggers and accurate (~1 arcmin within a few seconds; ~1'' within a few minutes) **high-energy transients for follow-up with next-generation optical-NIR (E-ELT, JWST if still operating), radio (SKA), X-rays (ATHENA), TeV (CTA) telescopes; synergy with LSST**

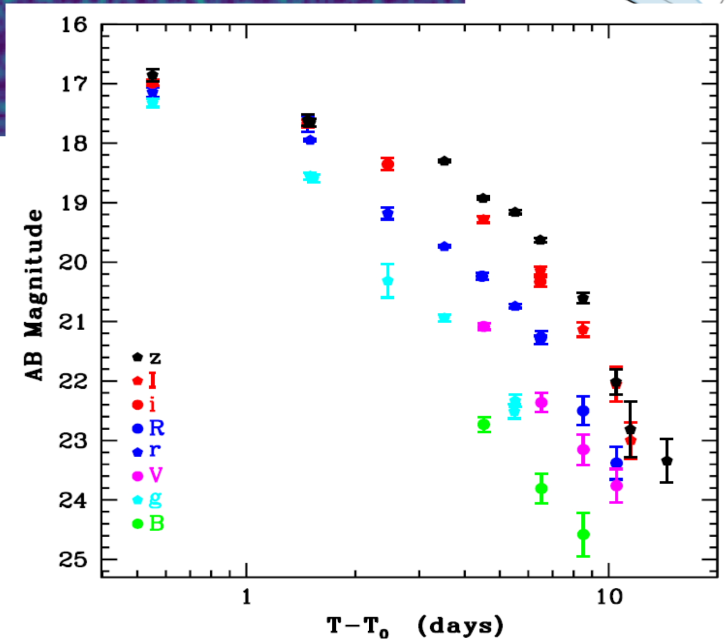


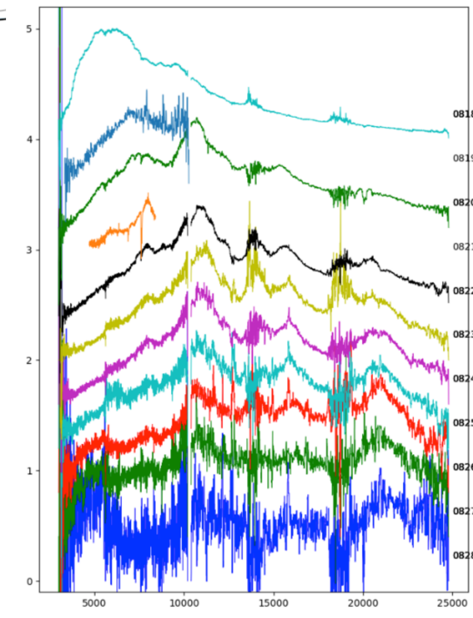
- Provide a fundamental step forward in the comprehension of the physics of various classes of transients and **fill the present gap in the discovery space of new classes of transients events**

LIGO, Virgo, and partners make first detection of gravitational waves and light from colliding neutron stars



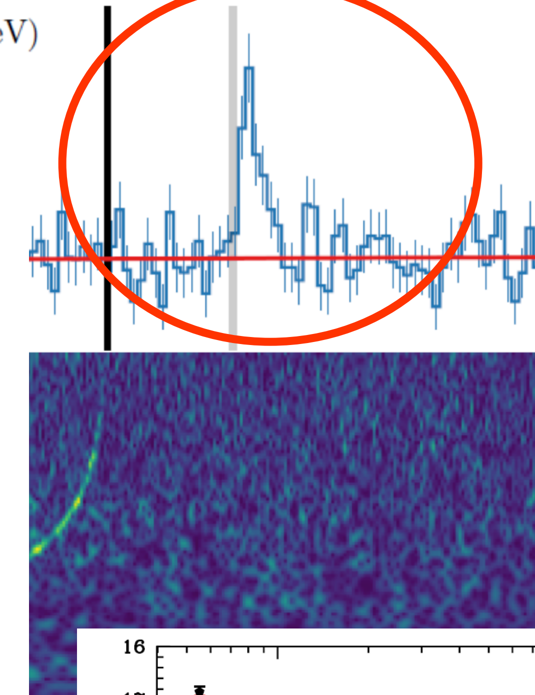






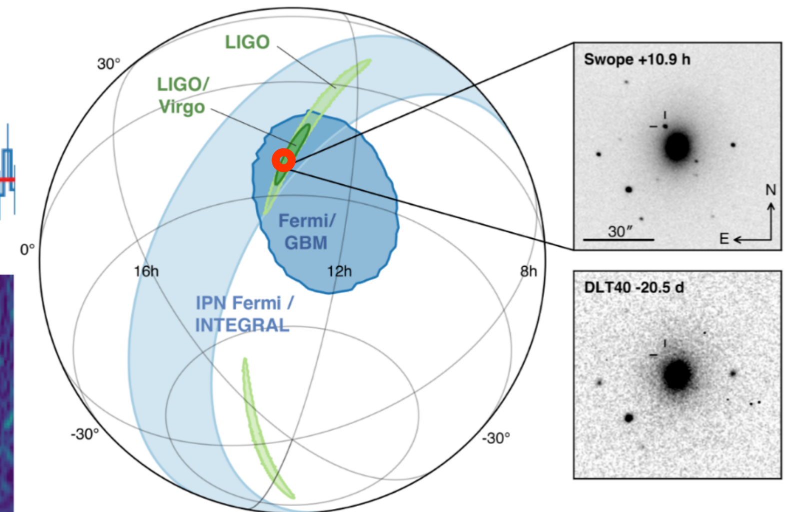
LIGO, Virgo, and partners make first detection of gravitational waves and light from colliding neutron stars

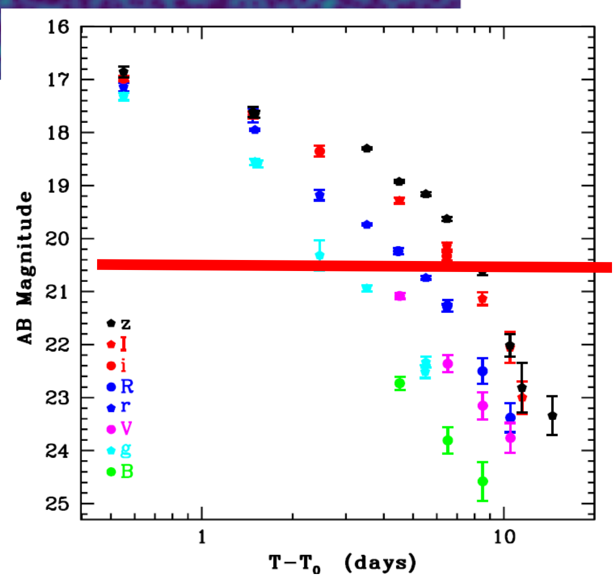
Lightcurve from *Fermi*/GBM (50 – 300 keV)

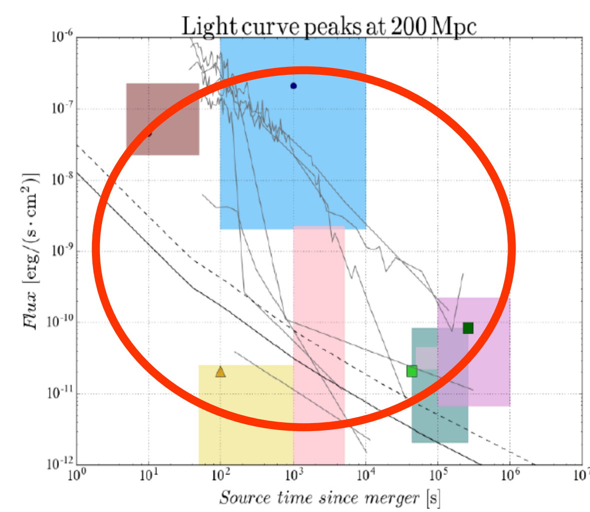


THESEUS:

- ✓ short GRB detection over large FOV with arcmin localization
- ✓ Kilonova detection, arcsec localization and characterization
- ✓ Possible detection of weaker isotropic X-ray emission

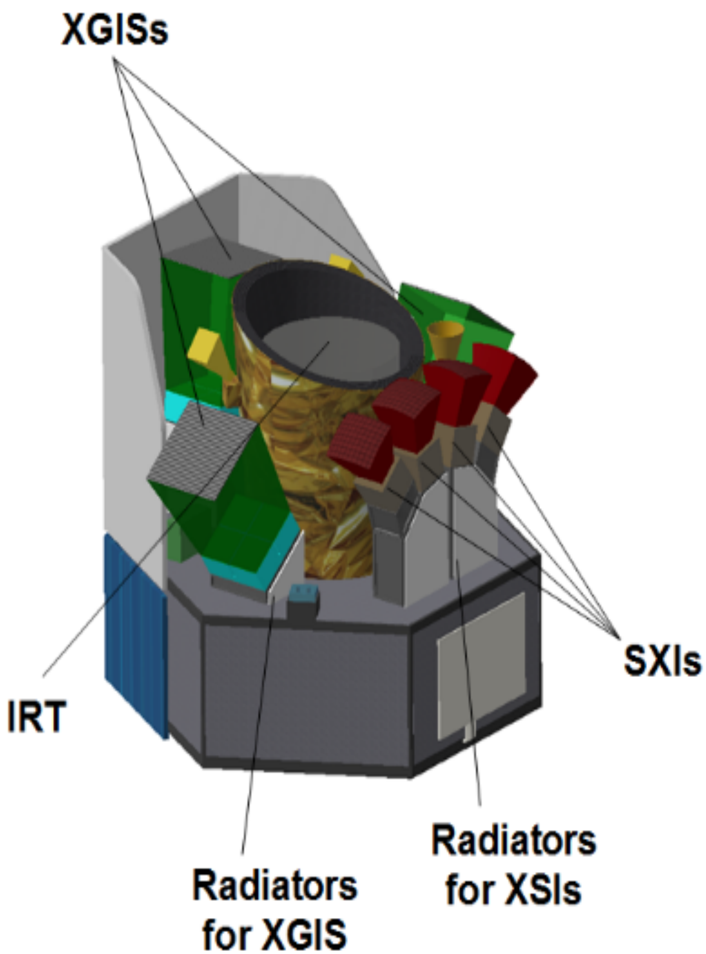






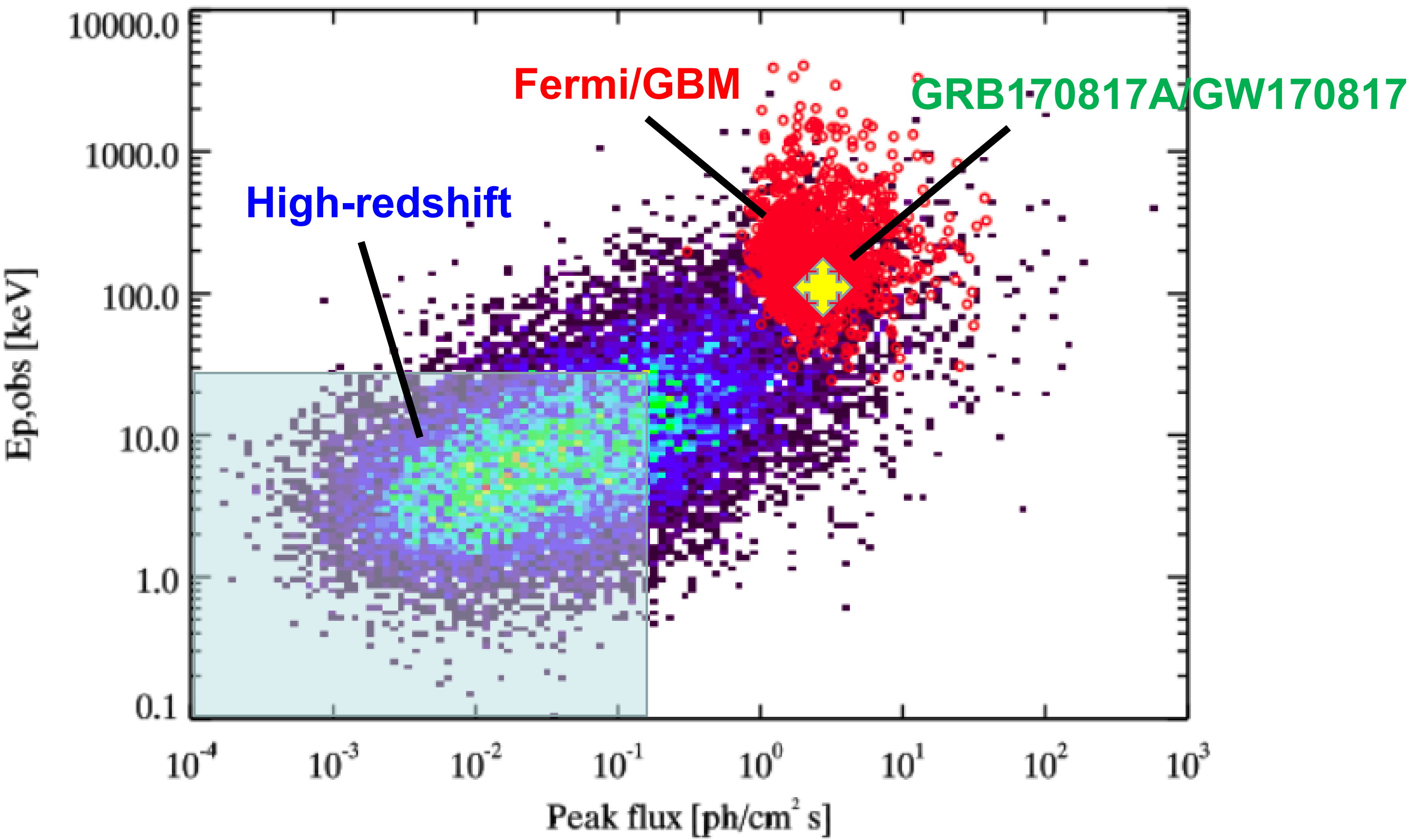
THESEUS mission concept

- **Soft X-ray Imager (SXI):** a set of four sensitive lobster-eye telescopes observing in **0.3 - 5 keV band, total FOV of ~1sr with source location accuracy 0.5-1';**
- **X-Gamma rays Imaging Spectrometer (XGIS,)**: 3 coded-mask X-gamma ray cameras using bars of Silicon diodes coupled with CsI crystal scintillators observing in **2 keV – 10 MeV band, a FOV of ~2-4 sr, overlapping the SXI, with ~5' GRB location accuracy** in 2-30 (150) keV
- **InfraRed Telescope (IRT)**: a 0.7m class IR telescope observing in the **0.7 – 1.8 μm band, providing a 10'x10' FOV, with both imaging and moderate resolution spectroscopy capabilities (-> redshift)**

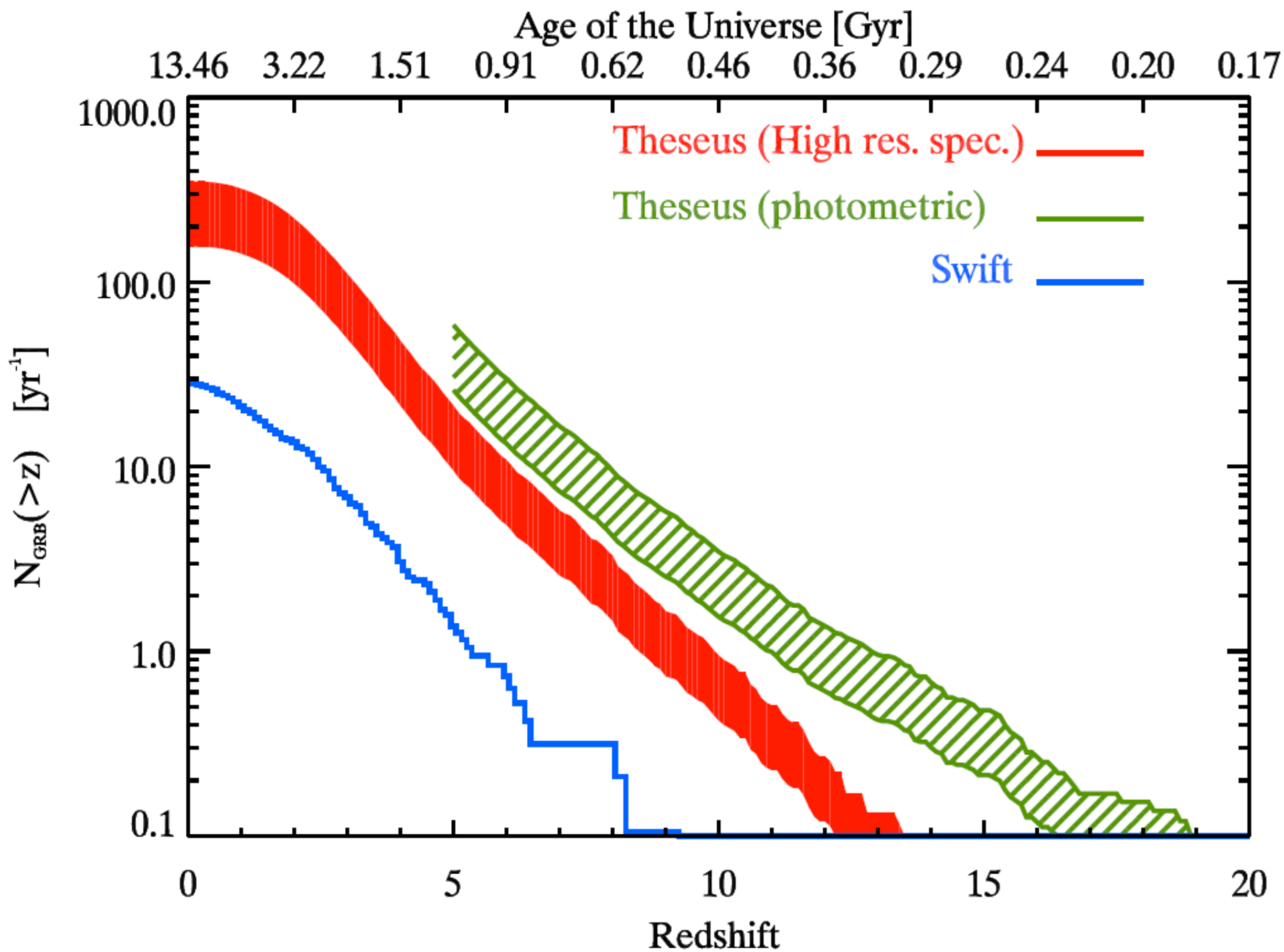


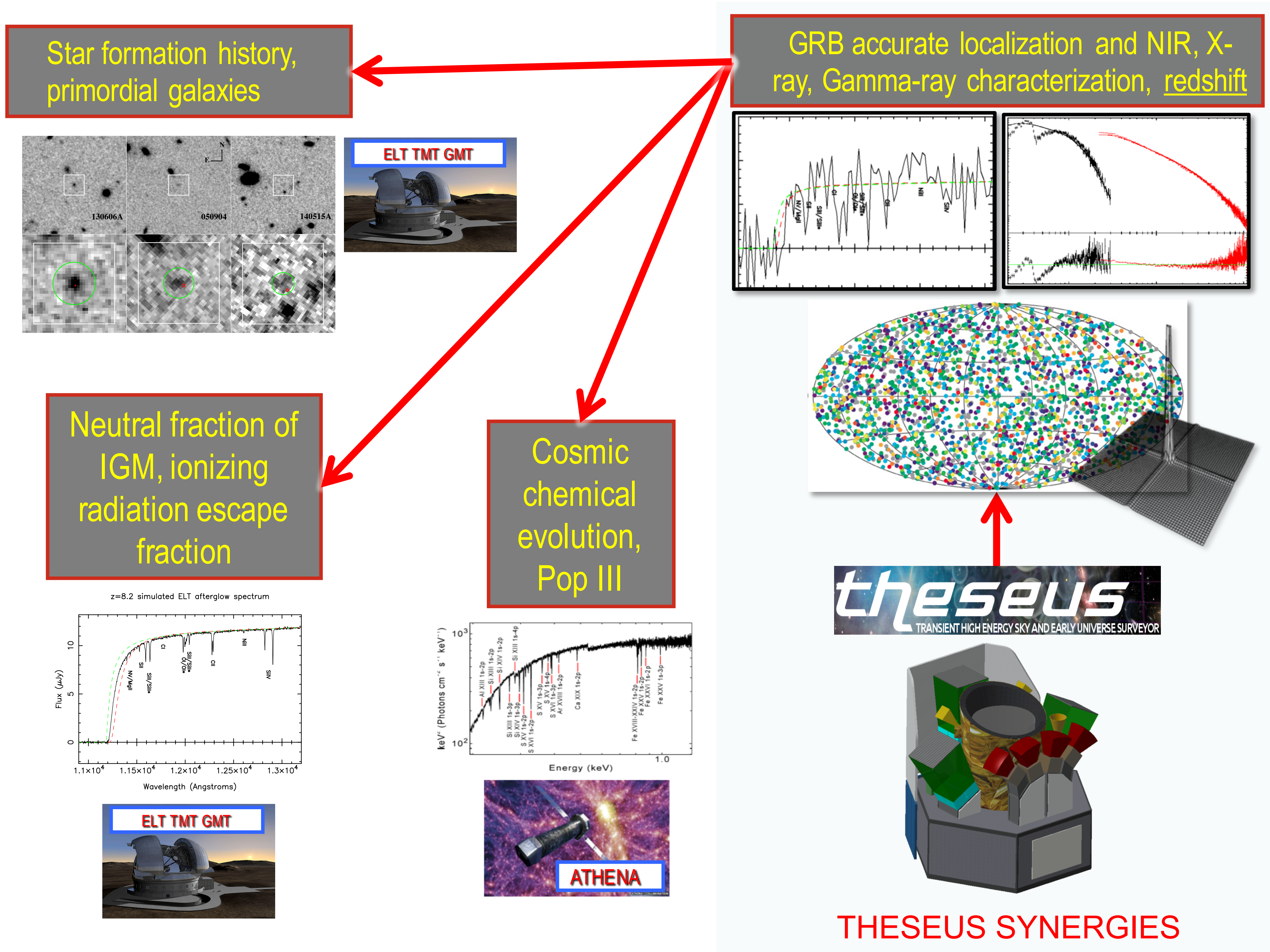
LEO (< 5°, ~600 km)
Rapid slewing bus
Prompt downlink

❑ THESEUS will have the ideal combination of instrumentation and mission profile for detecting all types of GRBs (long, short/hard, weak/soft, high-redshift), localizing them from a few arcmin down to arsec and measure the redshift for a large fraction of them



❑ Shedding light on the early Universe with GRBs




Star formation history, primordial galaxies
GRB accurate localization and NIR, X-ray, Gamma-ray characterization, redshift
N
E
130606A
050904
140515A
ELT TMT GMT
Neutral fraction of IGM, ionizing radiation escape fraction
Cosmic chemical evolution, Pop III
z=8.2 simulated ELT afterglow spectrum
Flux (μJy)
Wavelength (Angstroms)
keV² (Photons cm⁻² s⁻¹ keV⁻¹)
Energy (keV)
ELT TMT GMT
ATHENA
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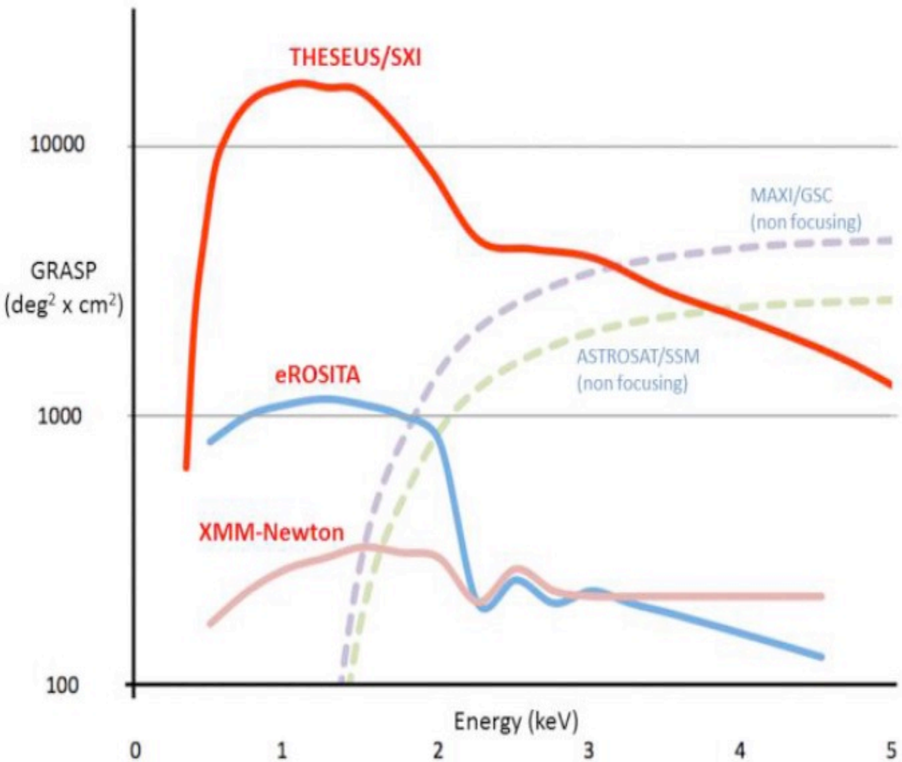
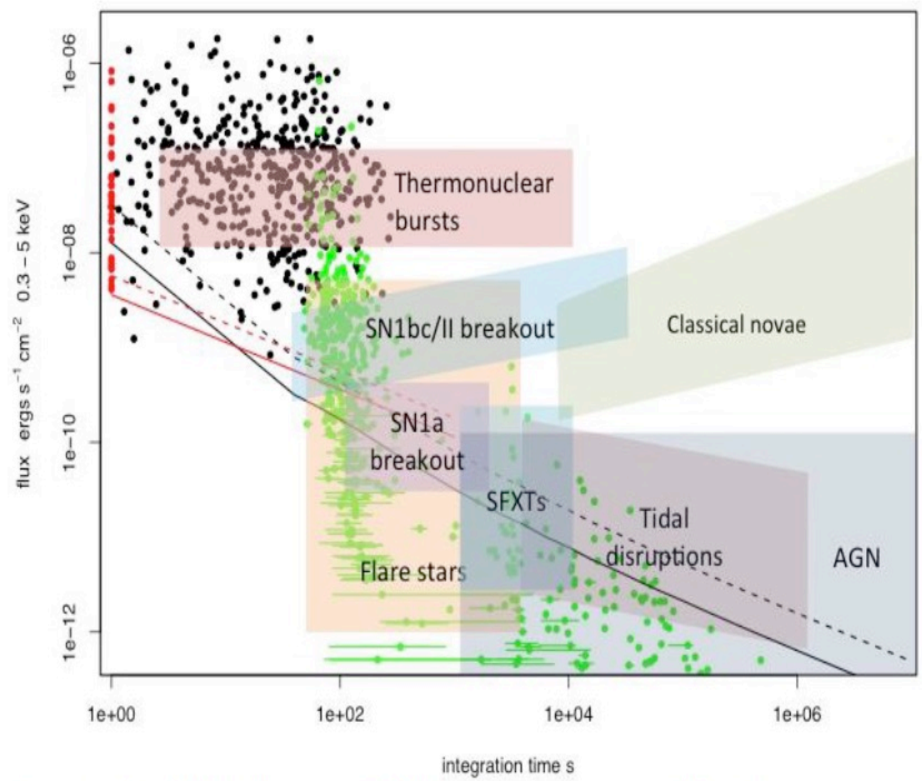
- THESEUS will also detect and localize down to 0.5-1 arcmin the soft X-ray short/long GRB afterglows, of NS-NS mergers and of many classes of galactic and extra-galactic transients

- For several of these sources, THESEUS/IRT may provide detection and study of associated NIR emission, location within 1 arcsec and redshift

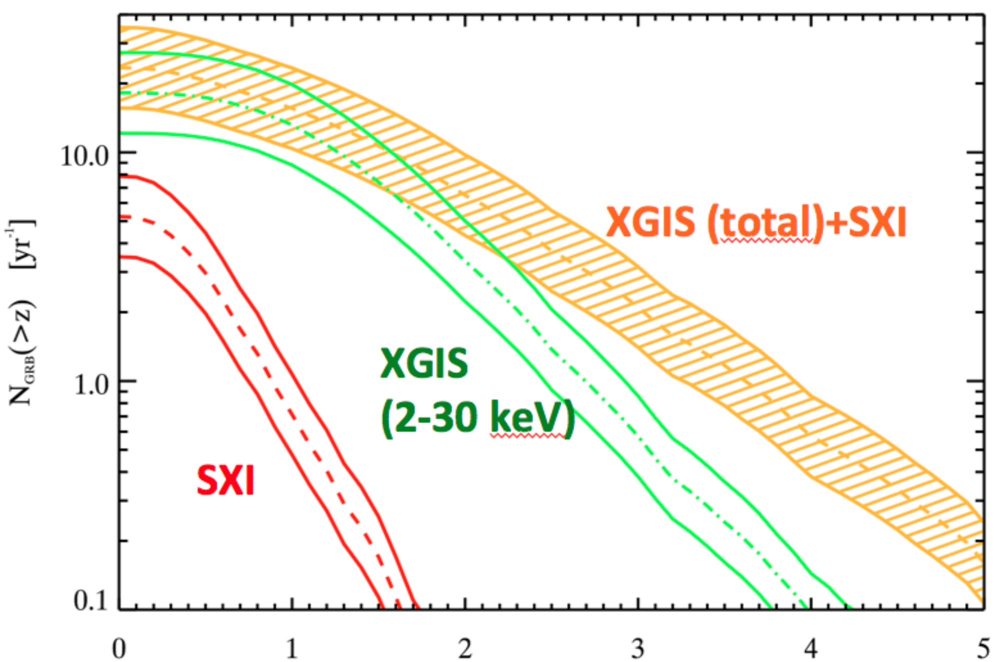


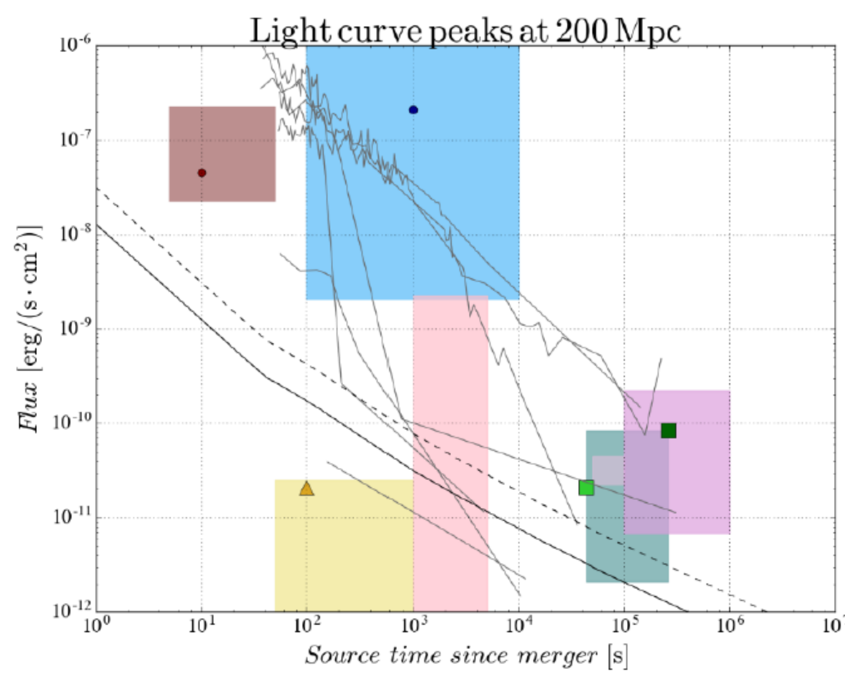


❑ GW/multi-messenger and time-domain astrophysics

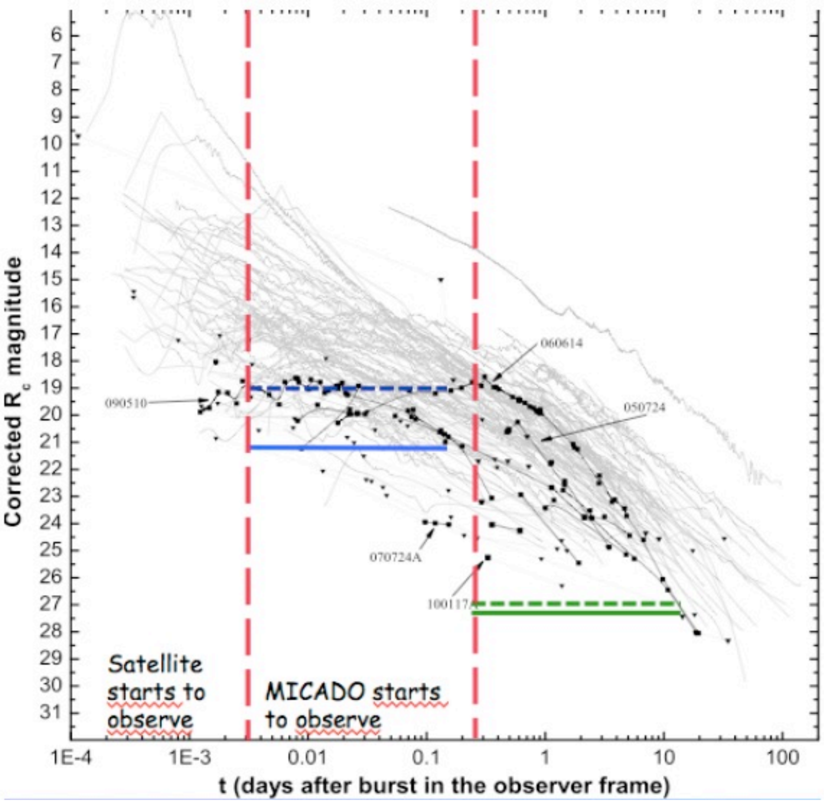
GW transient sources that will be monitored by THESEUS include **NS-NS / NS-BH mergers**:

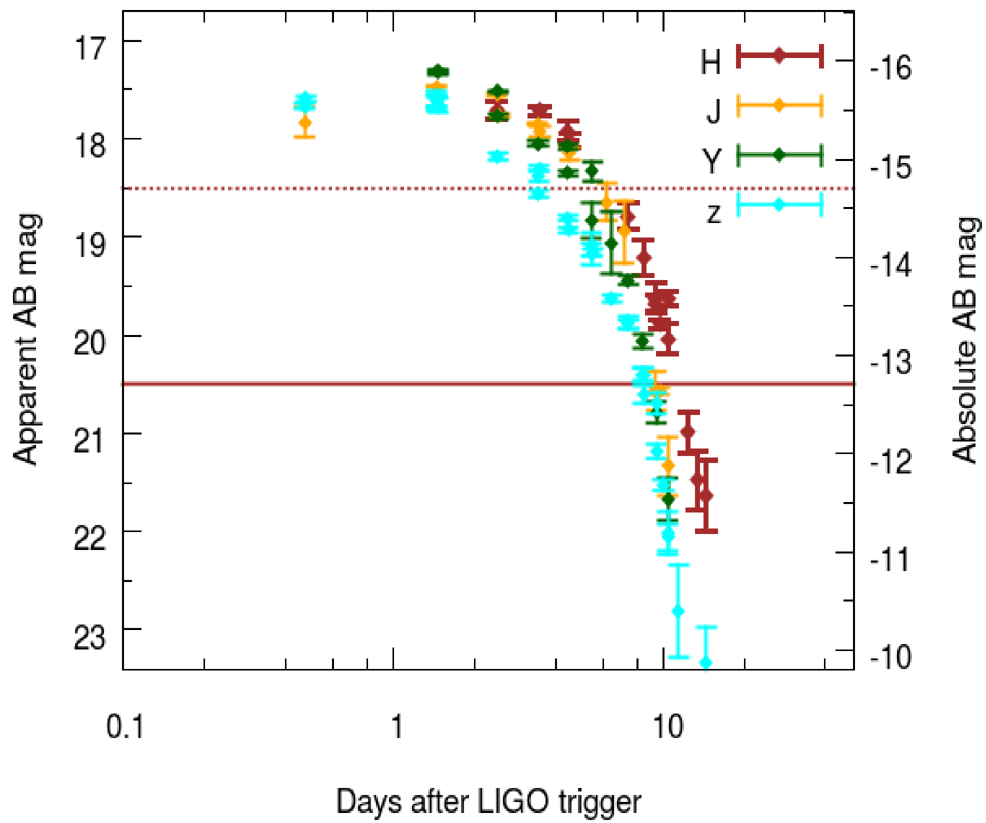
- ❑ **collimated** on-axis and off-axis prompt gamma-ray emission from short GRBs
- ❑ Optical/NIR and soft X-ray **isotropic** emissions from kilonovae, off-axis afterglows and, for NS-NS, from newly born ms magnetar spindown





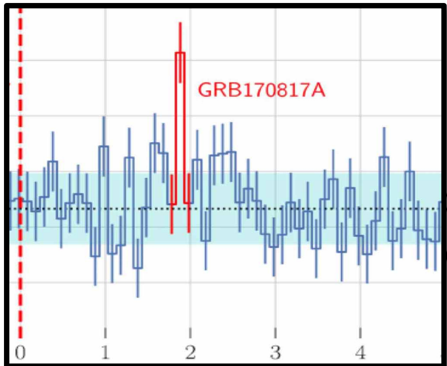
❑ Detection, study and arcsecond localization of afterglow and kilonova emission from shortGRB/GW events with THESEUS/IRT

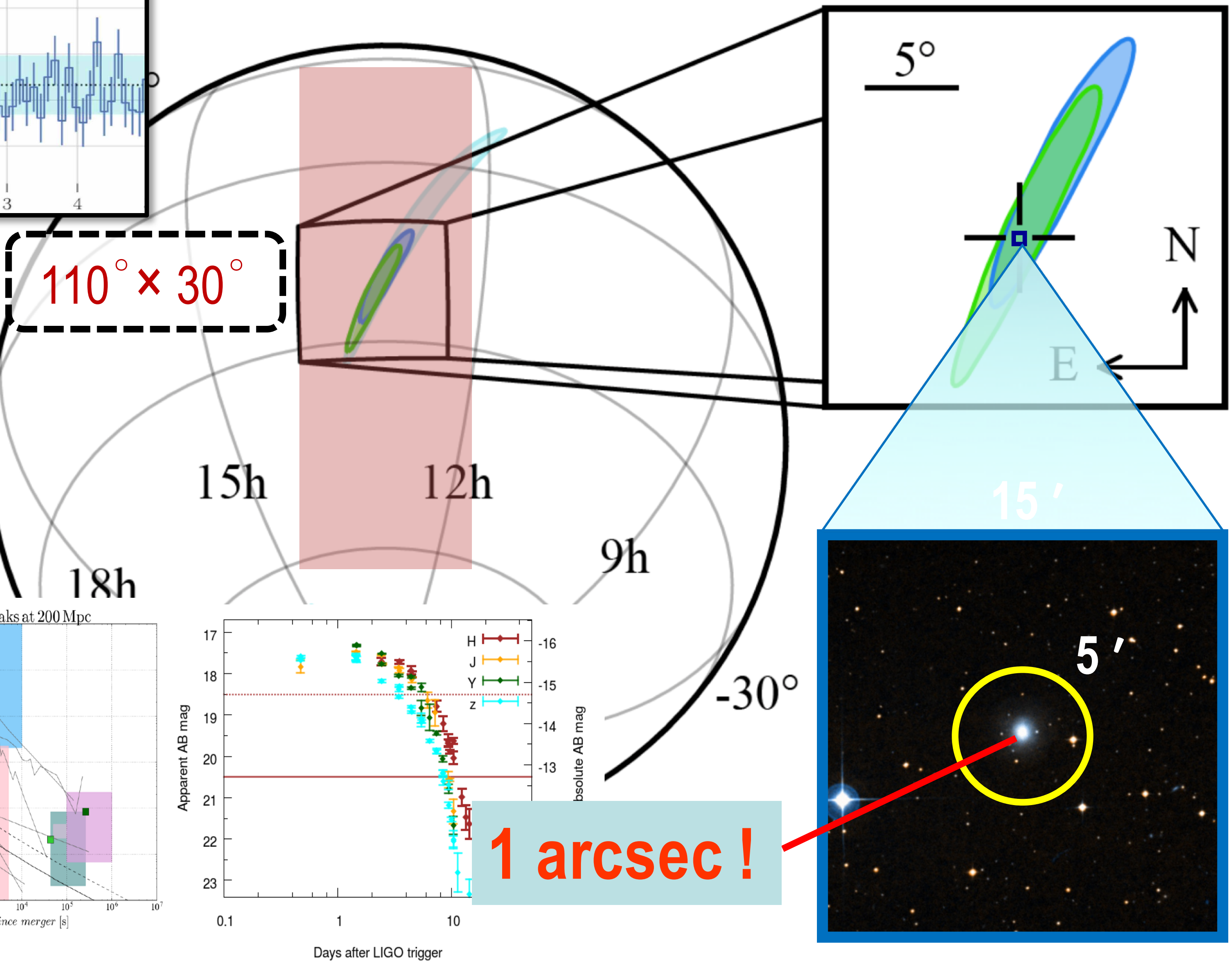


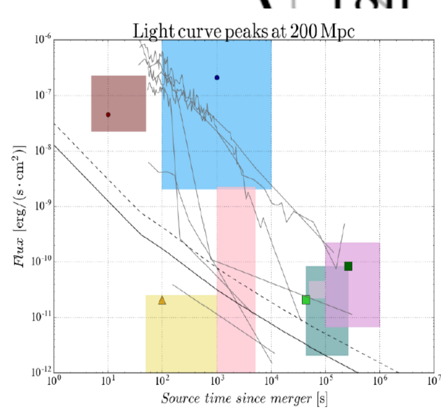


Precise localization is mandatory to activate large ground-based telescopes as VLT or ELT from which detailed spectral analysis will reveal the intrinsic nature of these newly discovered phenomena

❑ Promptly and accurately localizing e.m. counterparts to GW events with THESEUS







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TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR

- ***THESEUS*** **Core Science is based on two pillars:**
  - probe the **physical properties of the early Universe**, by discovering and exploiting the population of high redshift GRBs.
  - provide an **unprecedented deep monitoring** of the soft X-ray transient Universe, providing a fundamental contribution to multi-messenger and time domain astrophysics in the early 2030s (synergy with aLIGO/aVirgo, eLISA, ET, Km3NET and EM facilities e.g., LSST, E-ELT, SKA, CTA, ATHENA).

- ***THESEUS*** **Observatory Science includes:**
  - study of thousands of faint to bright X-ray sources by exploiting the **unique simultaneous availability of broad band X-ray and NIR observations**
  - provide a **flexible follow-up observatory** for fast transient events with multi-wavelength ToO capabilities and **guest-observer programmes**.

In summary

- THESEUS, submitted to ESA/M5 by a large European collaboration with strong interest by international partners (e.g., US) will fully exploit GRBs as powerful and unique tools to investigate the early Universe and will provide us with unprecedented clues to GRB physics and sub-classes.

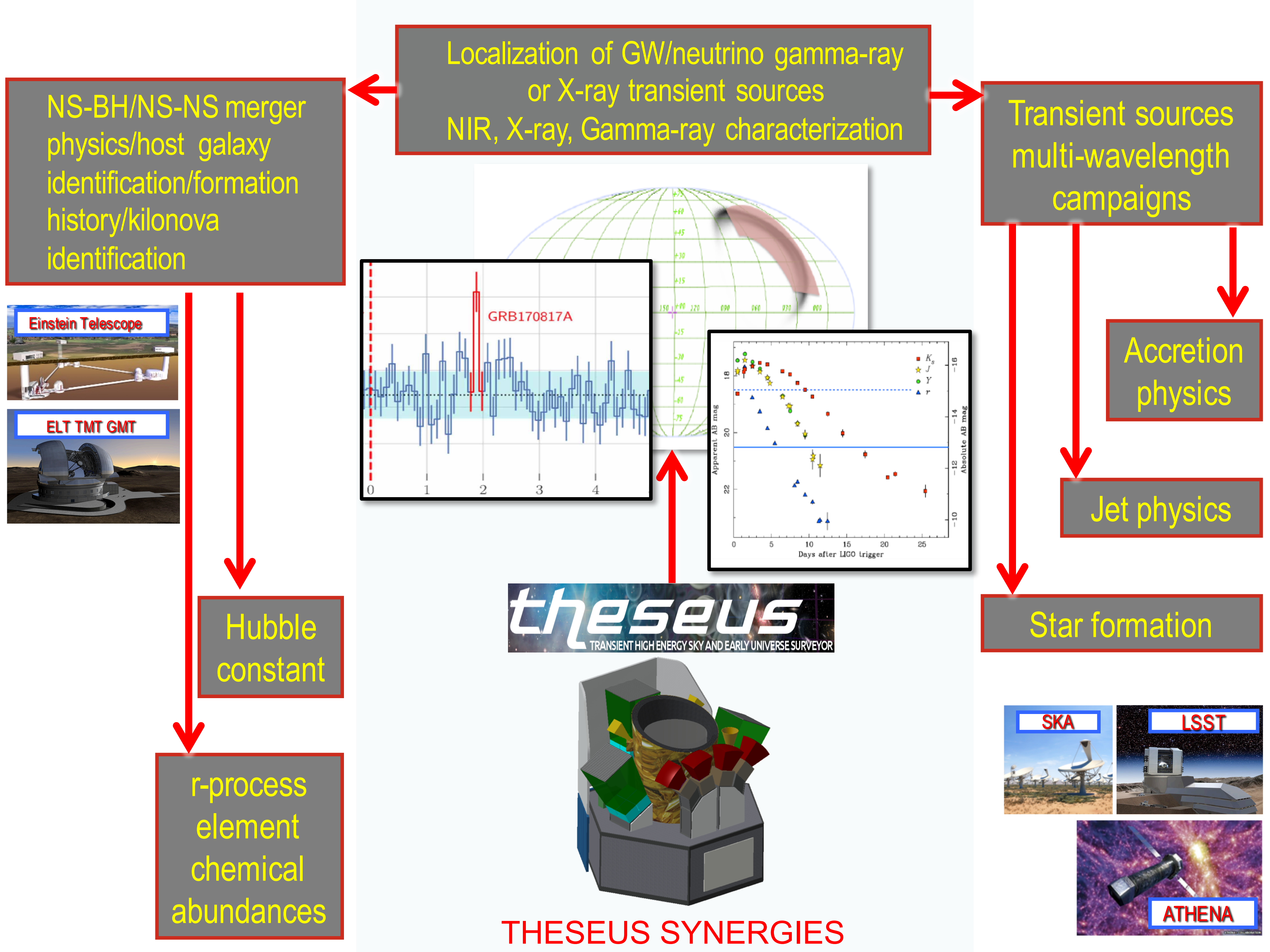
- THESEUS will also play a fundamental role for GW/multi-messenger and time domain astrophysics at the end of next decade, also by providing a flexible follow-up observatory for fast transient events with multi-wavelength ToO capabilities and guest-observer programmes

- THESEUS is a unique occasion for fully exploiting the European and Italian leadership in time-domain and multi-messenger astrophysics and in key-enabling technologies

- THESEUS observations will impact on several fields of astrophysics, cosmology and fundamental physics and will enhance importantly the scientific return of next generation multi messenger (aLIGO/aVirgo, LISA, ET, or Km3NET;) and e.m. facilities (e.g., LSST, E-ELT, SKA, CTA, ATHENA)

- Call for participating THESEUS scientific WGs will be issued very soon; THESEUS science session at EWASS 19 in Lyon; Theseus Consortium meeting in Bologna on July 3-5; THESEUS International Conference in Malaga on Spring 2020

Back-up slides



Localization of GW/neutrino gamma-ray or X-ray transient sources NIR, X-ray, Gamma-ray characterization
NS-BH/NS-NS merger physics/host galaxy identification/formation history/kilonova identification
Transient sources multi-wavelength campaigns
Einstein Telescope
ELT TMT GMT
GRB170817A
Days after LIGO trigger
Apparent AB mag
Absolute AB mag
Hubble constant
r-process element chemical abundances
Accretion physics
Jet physics
Star formation
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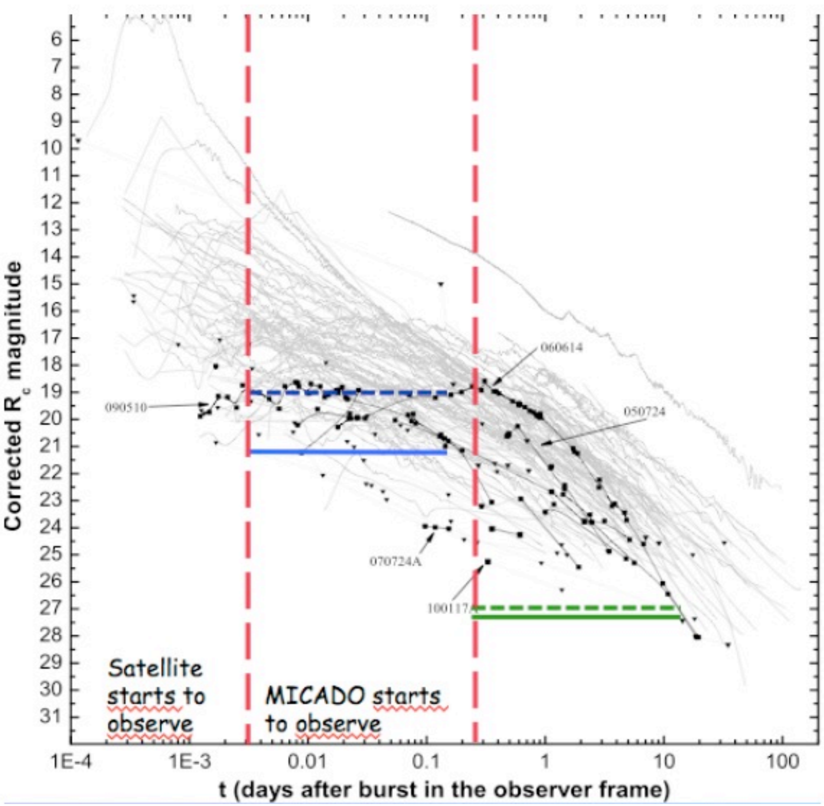
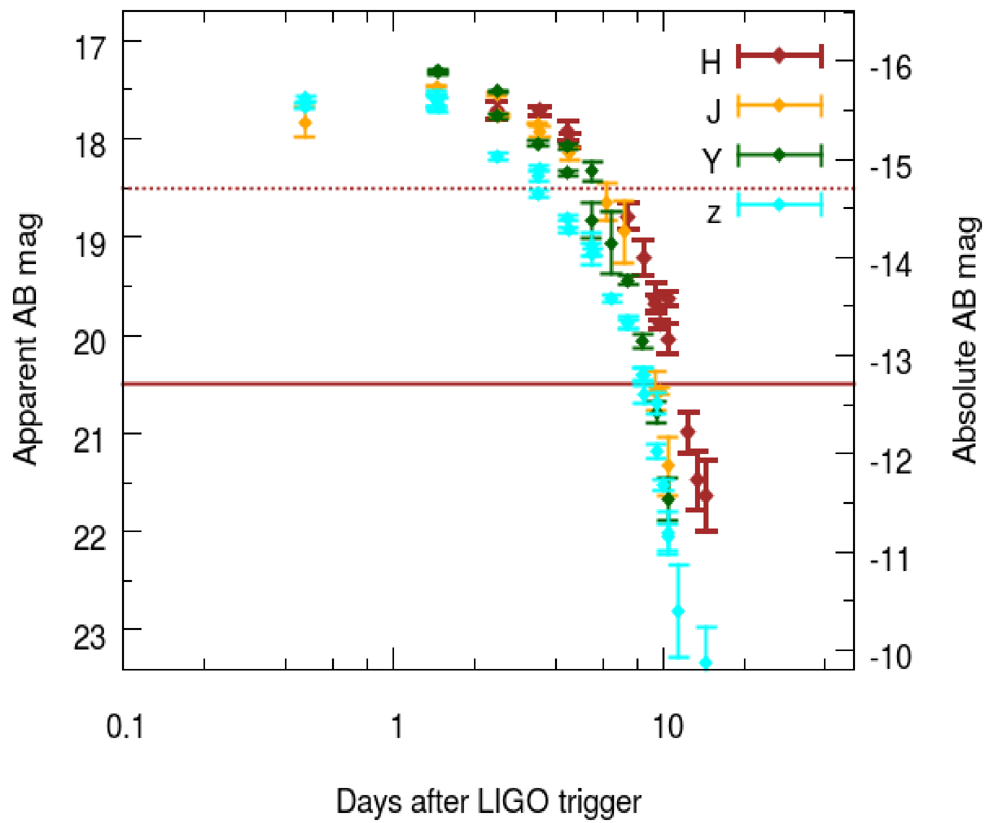
SKA
LSST
ATHENA
THESEUS SYNERGIES

❑ Detection, study and arcsecond localization of afterglow and kilonova emission from shortGRB/GW events with THESEUS/IRT





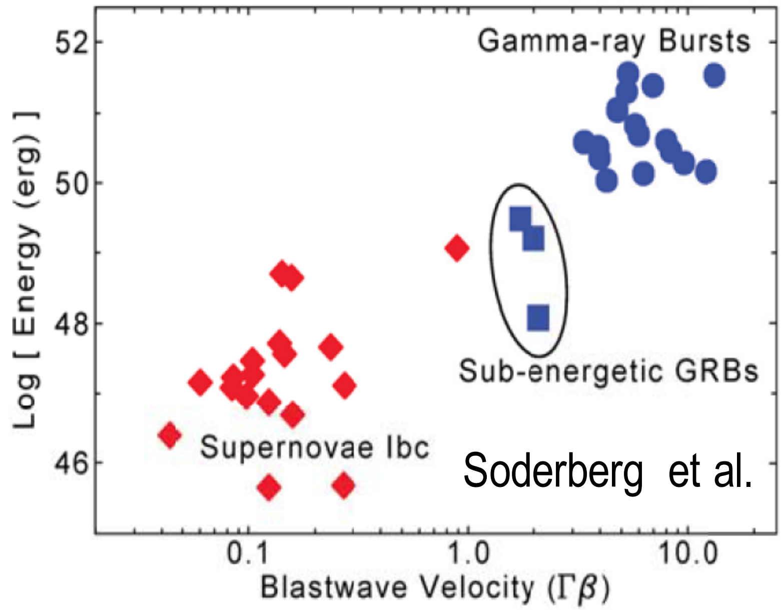
Precise localization is mandatory to activate large ground-based telescopes as VLT or ELT from which detailed spectral analysis will reveal the intrinsic nature of these newly discovered phenomena

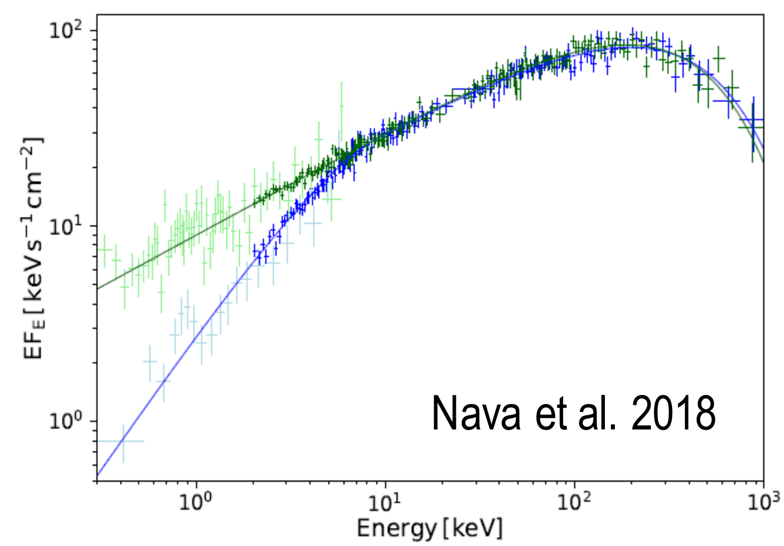
❑ Time-domain astronomy and GRB physics

- survey capabilities of transient phenomena similar to the Large Synoptic Survey Telescope (LSST) in the optical: a remarkable scientific sinergy can be anticipated.

- substantially increased detection rate and characterization of sub-energetic GRBs and X-Ray Flashes;

- unprecedented insights in the physics and progenitors of GRBs and their connection with peculiar core-collapse Sne;



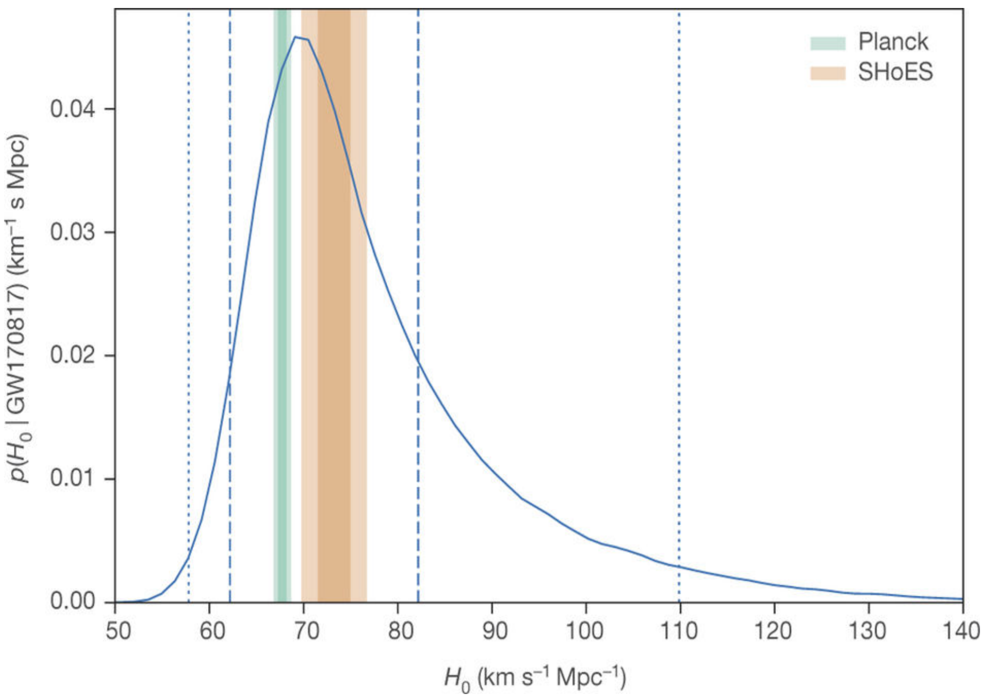


❑ GW/multi-messenger and time-domain astrophysics

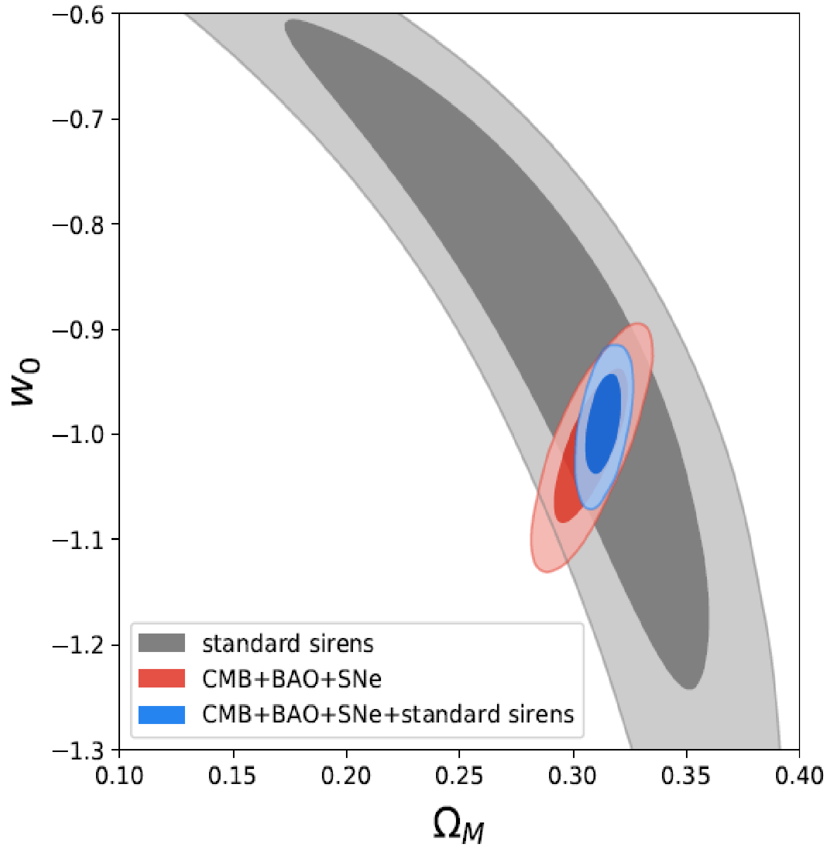
GW transient sources that will be monitored by THESEUS include:

- ❑ **NS-NS / NS-BH mergers:**
  - ❑ **collimated** EM emission from short GRBs and their afterglows (rate up to 20/yr for 3G GW detectors as Einstein Telescope)
  - ❑ Optical/NIR and soft X-ray **isotropic** emissions from **macronovae, off-axis afterglows** and, for NS-NS, from newly born ms magnetar spindown (rate of GW detectable NS-NS or NS-BH systems, i.e. dozens-hundreds/yr)
- ❑ Core collapse of massive stars: Long GRBs, LLGRBs, ccSNe (much more uncertain predictions in GW energy output, possible rate of ~1/yr)
- ❑ Flares from isolated NSs: Soft Gamma Repeaters (although GW energy content is ~0.01%-1% of EM counterpart)

- **THESEUS measurements + sinergy with large e.m. facilities -> substantial improvment of redshift estimate for e.m. counterparts of GW sources -> cosmology**

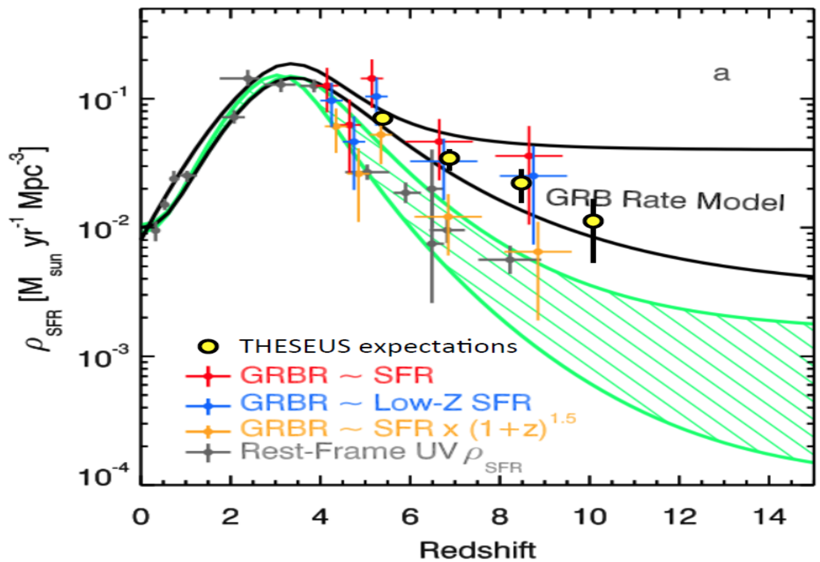


Estimating H0 with GW170817A (LVC 2017)

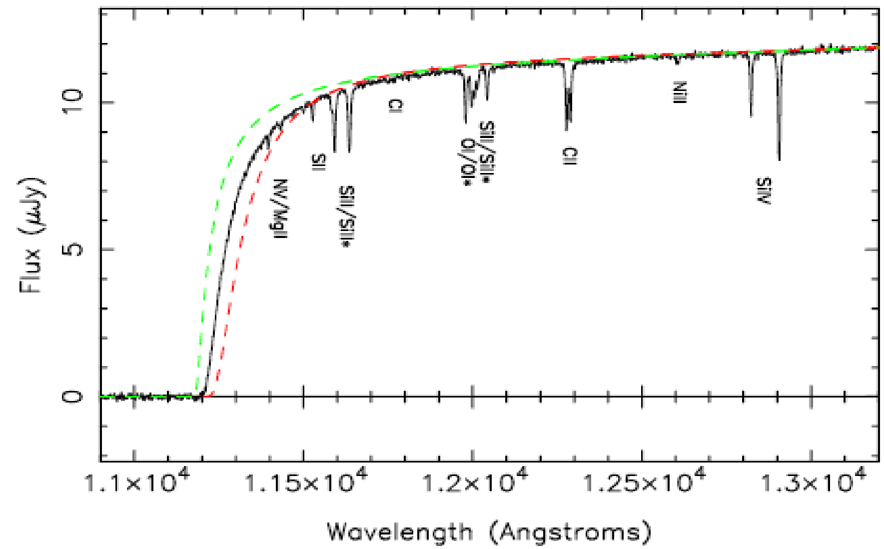


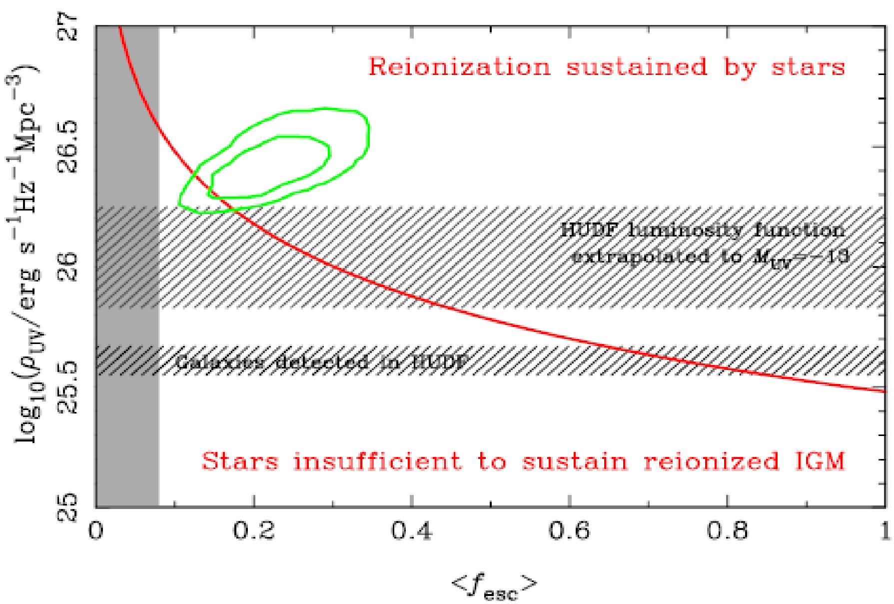
Investigating dark energy with a statistical sample of GW + e.m. (Sathyaprakash et al. 2019)

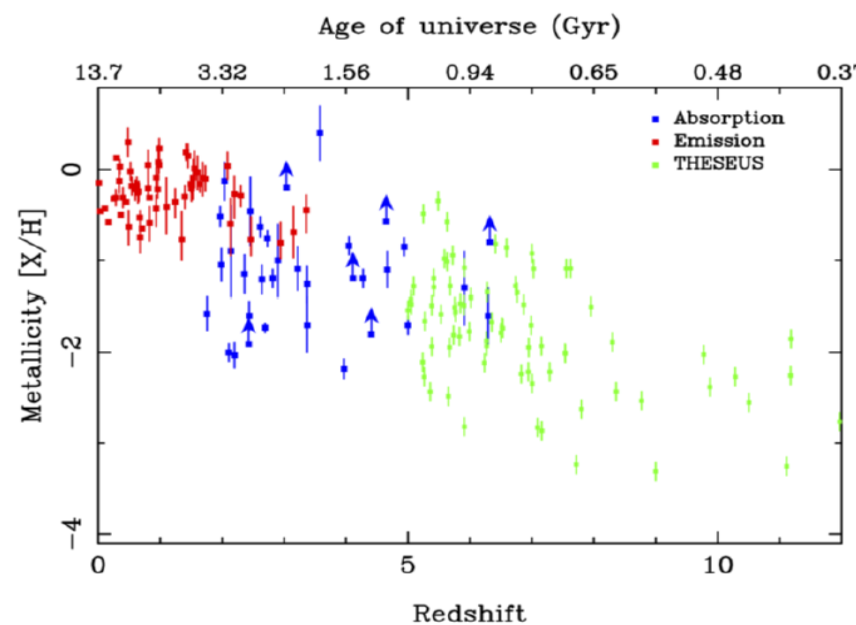
❑ Shedding light on the early Universe with GRBs



z=8.2 simulated E-ELT afterglow spectra

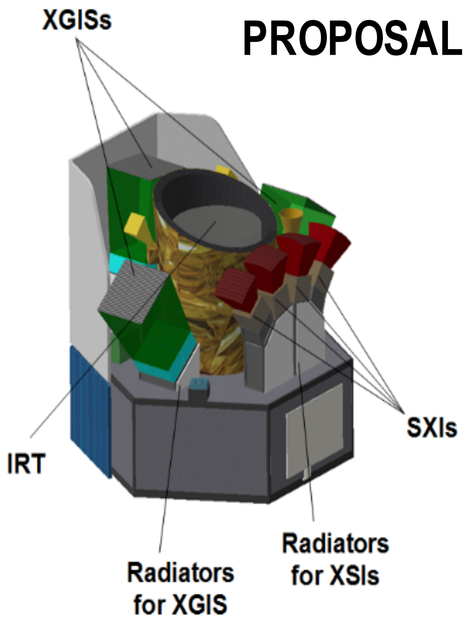




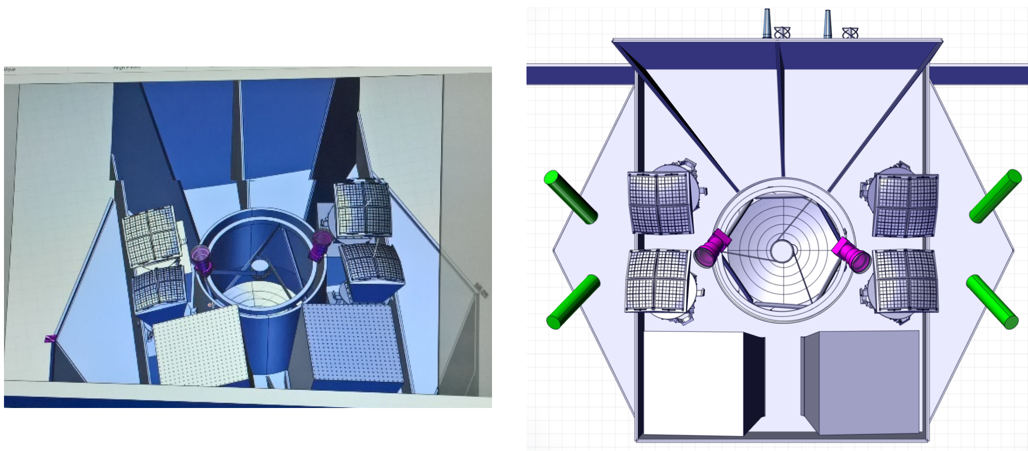


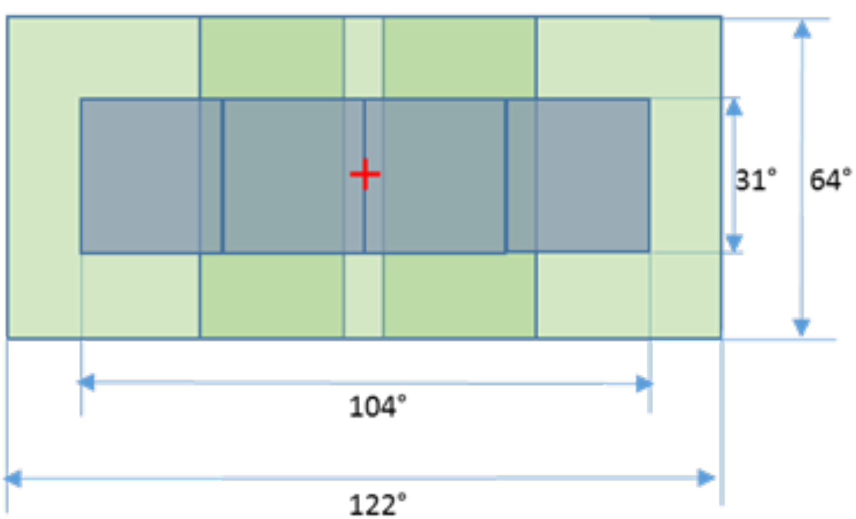
THESEUS mission concept: ESA study

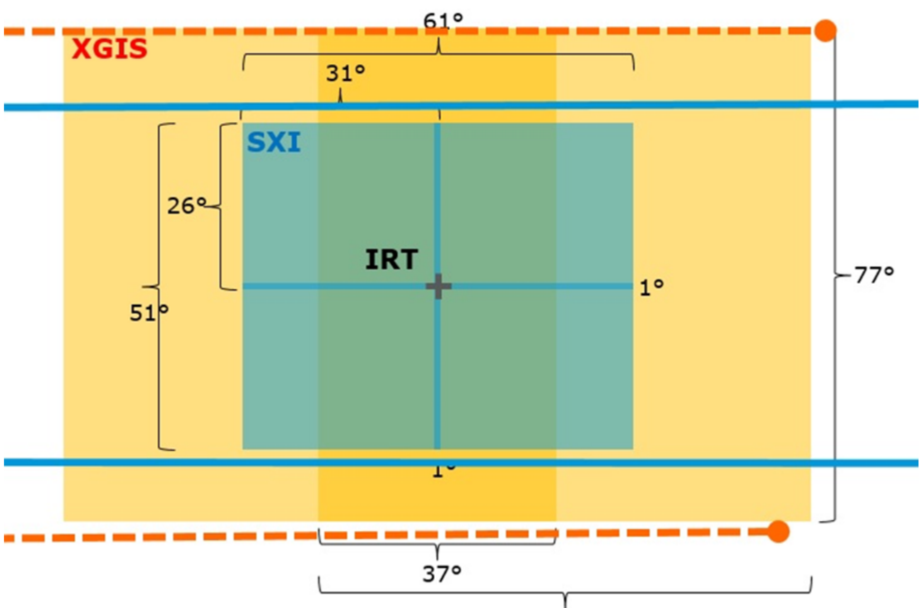
PROPOSAL



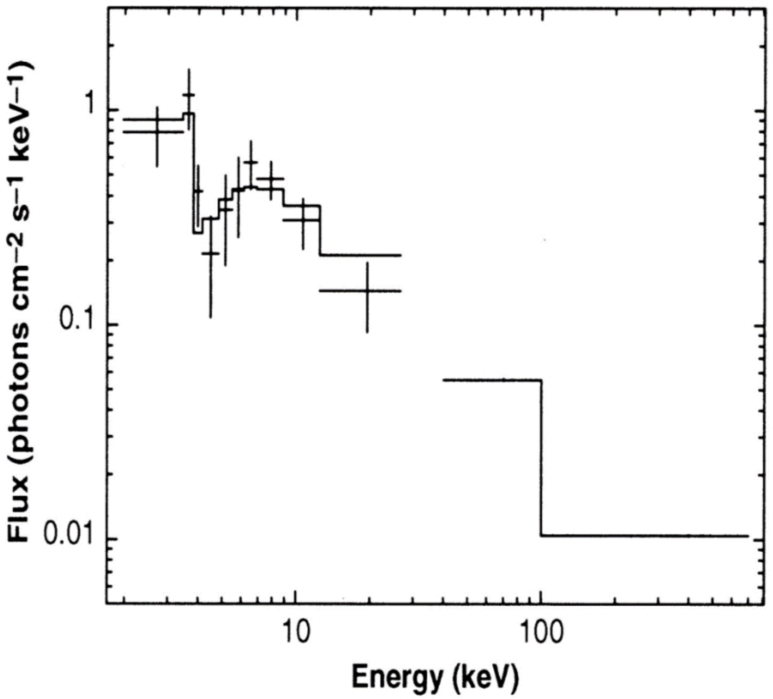
CDF STUDY



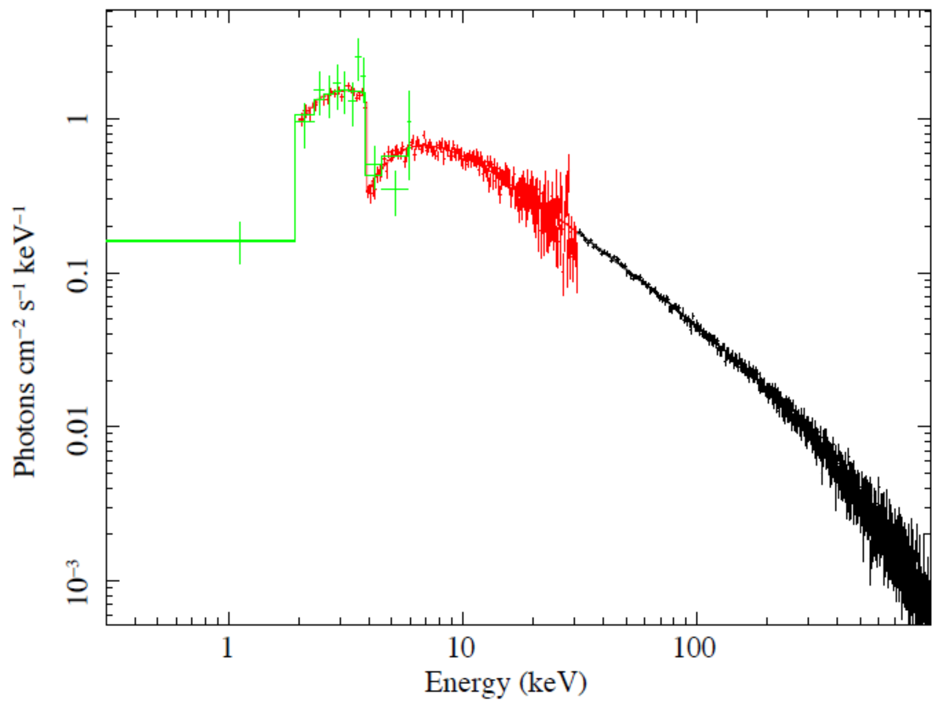




- Absorption features: the case of GRB990705 (edge at 3.8 keV -> redshifted neutral iron k-edge -> z = 0.85 -> confirmed by host galaxy spectroscopy: redshift estimate through X-ray spectroscopy (need energy resolution < ~1 keV in X-rays)

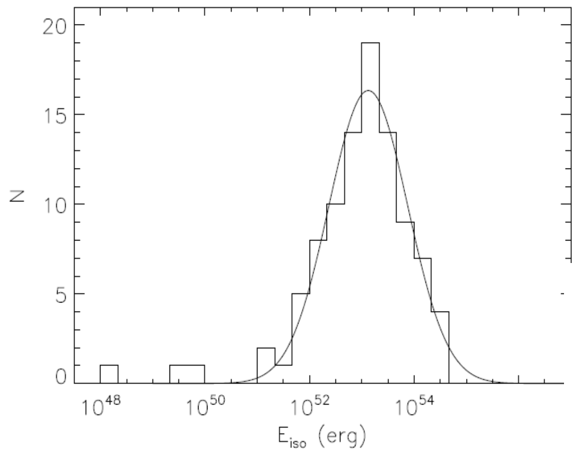


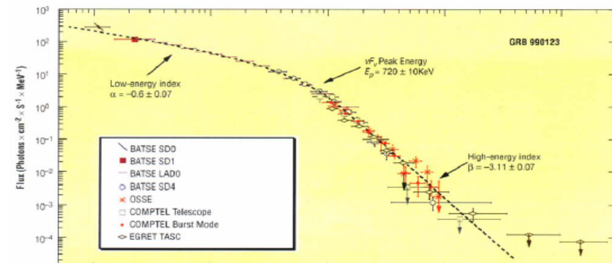
BeppoSAX WFC + GRBM
(Amati et al. 2000)

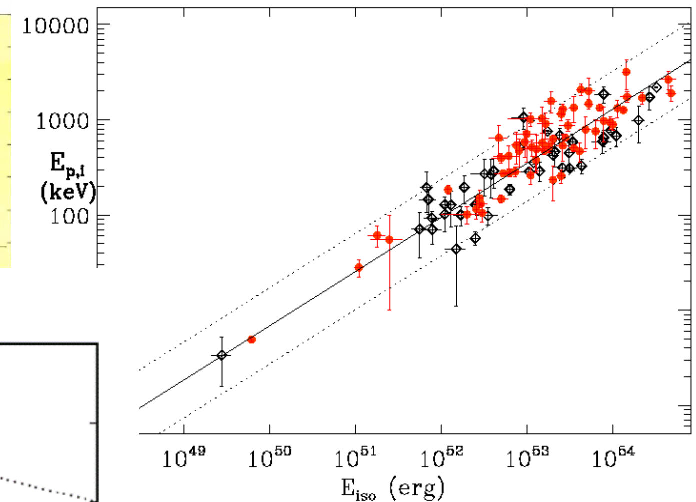


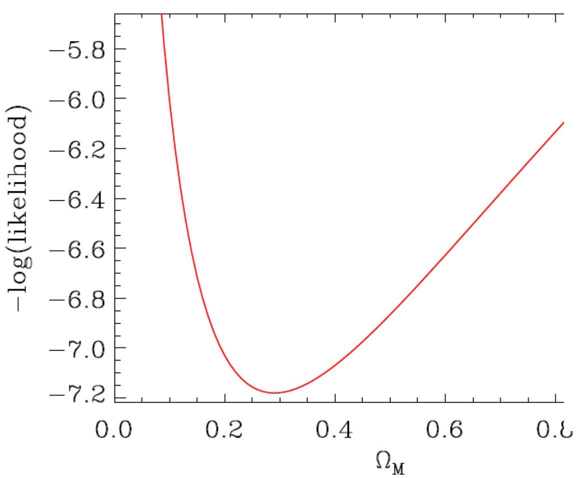
THESEUS SXI + XGIS
(Nava et al. 2018)

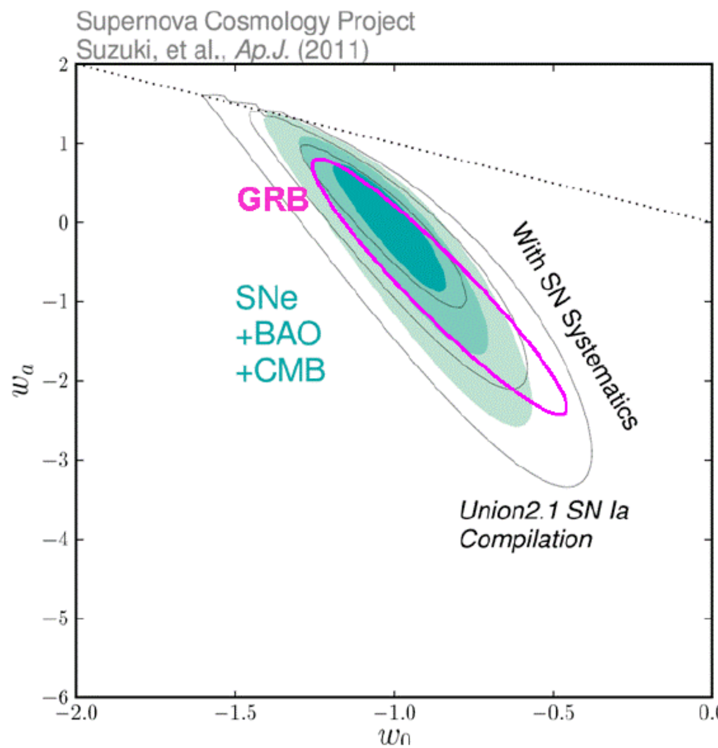
❑ measuring cosmological parameters with GRBs

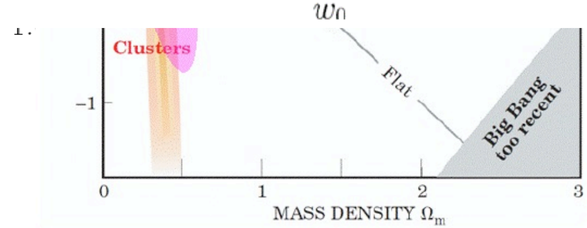


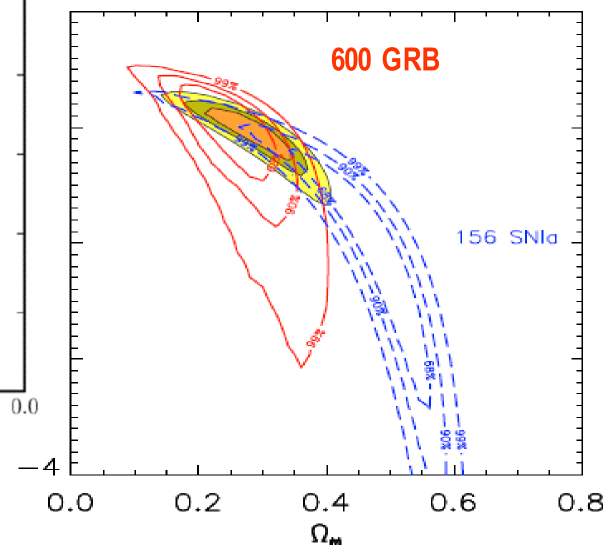








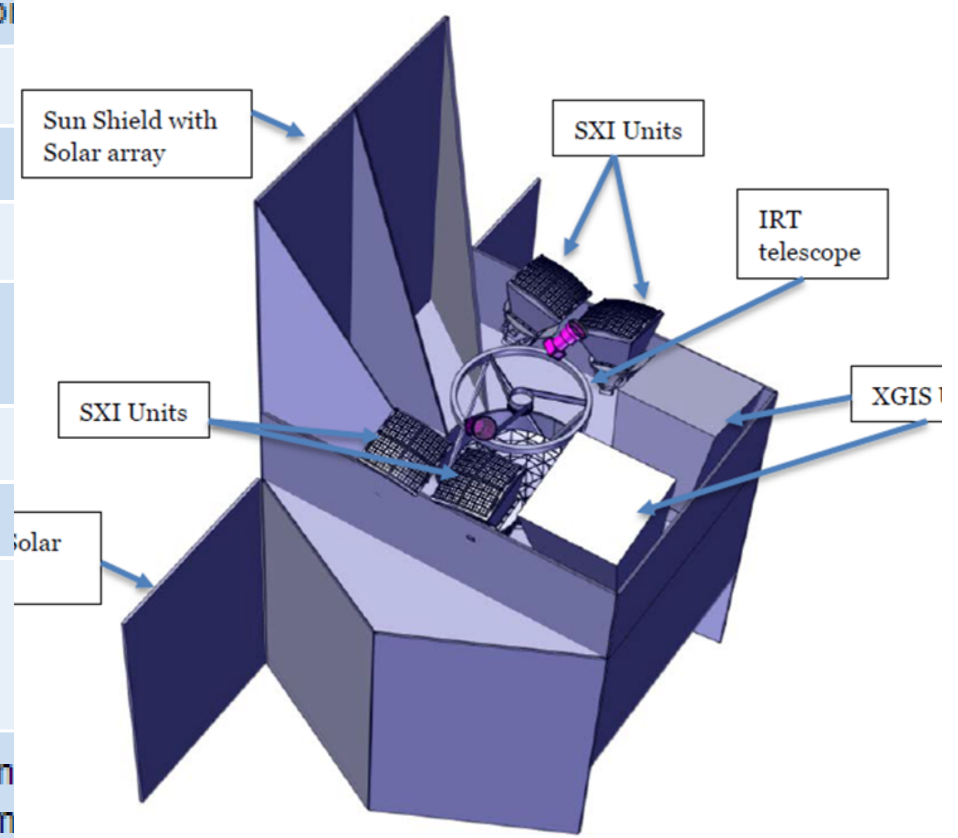




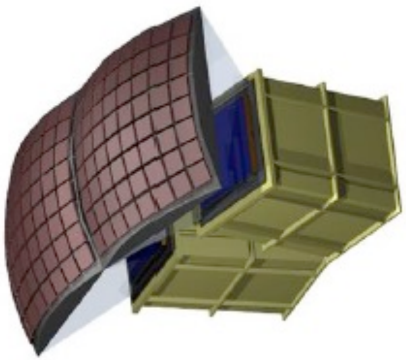
$$w(z) = w_0 + \frac{w_a z}{1+z}$$

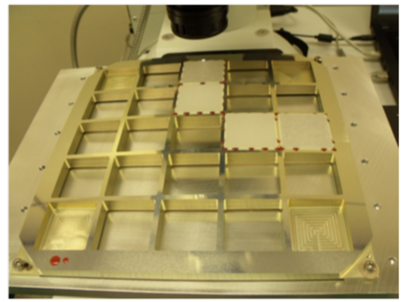
Mission profile and budgets

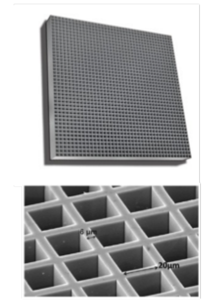
Launch vehicle	VEGA-C (backup Ariane62)
Launch date	2032 (night launch)
Lifetime	Nominal 3 years (consumables fo
Orbit	Circular LEO
Altitude	600 km
Inclination	5.4°
Ground stations	Malindi (backup Kourou) VHF SVOM network
Delta-V	225.8 m/s
Re-entry	Controlled re-entry (4 burns)
Mass	Dry mass w/ margin 1504 kg Wet mass 1702 kg Total (wet + adapter) 1697 kg
Dimensions	Launch conf.: 4.23 m x 3.02 m Deployed conf.: 4.23 m x 4.40 m
Payload	1x InfraRed Telescope (IRT) 2x X-Gamma-rays Imaging Spect 4x Soft X-ray Imager (SXI) 2x Radiation monitors

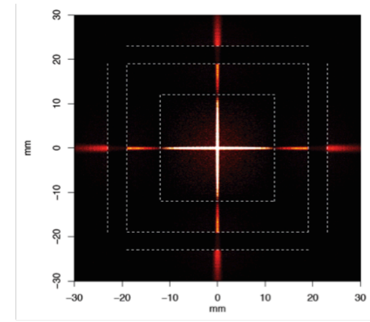


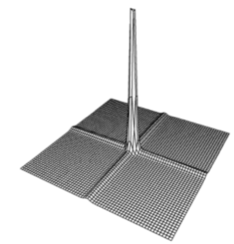
The Soft X-ray Imager (SXI)











4 DUs, each has a 31 x 26 degree FoV

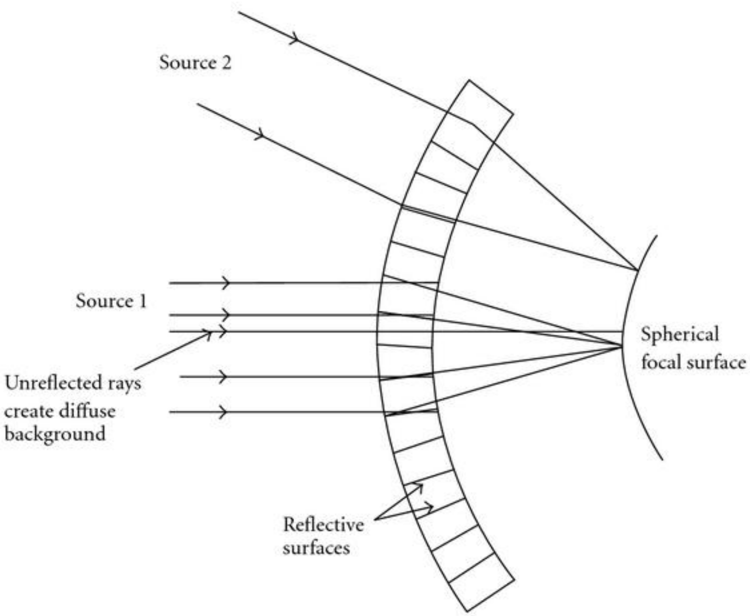
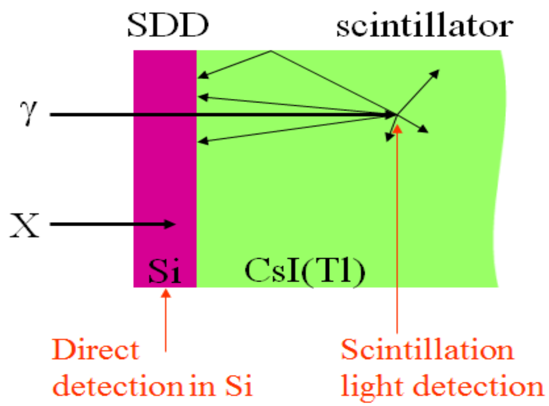
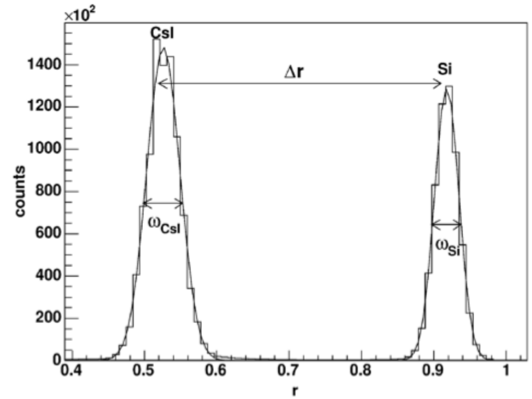


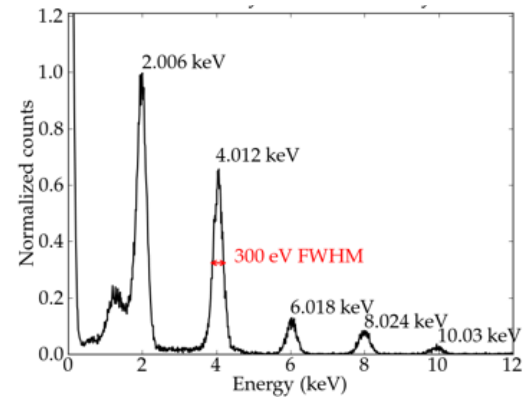
Table 4 : : SXI detector unit main physical characteristics

Energy band (keV)	0.3-5
Telescope type:	Lobster eye
Optics aperture (mm2)	320x320
Optics configuration	8x8 square pore MCPs
MCP size (mm2)	40x40
Focal length (mm)	300
Focal plane shape	spherical
Focal plane detectors	CCD array
Size of each CCD (mm2)	81.2x67.7
Pixel size (µm)	18
Pixel Number	4510 x 3758 per CCD
Number of CCDs	4
Field of View (square deg)	~1sr
Angular accuracy (best, worst) (arcsec)	(<10, 105)
Power [W]	27,8
Mass [kg]	40

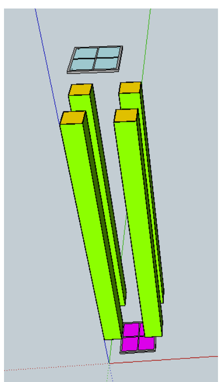
The X-Gamma-rays spectrometer (XGS)

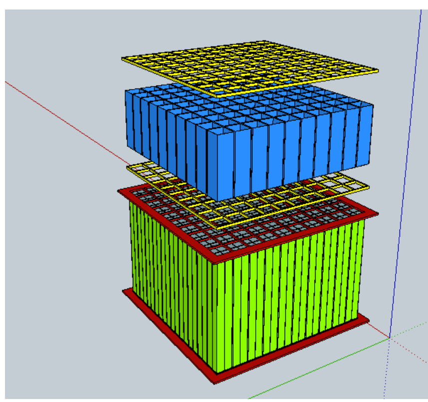


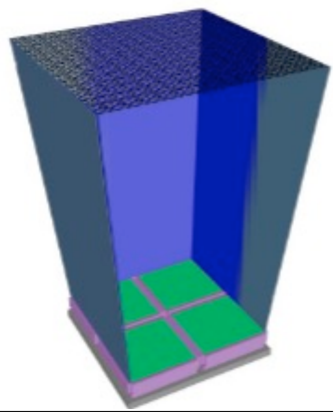




Energy band	*2 keV – 20 MeV*
# detection plane modules	*4*
# of detector pixel / module	*32x32*
pixel size (= mask element size)	*5x5 mm*
Low-energy detector (2-30 keV)	*Silicon Drift Detector 450 μm thick*
High energy detector (> 30 keV)	*CsI(Tl) (3 cm thick)*
Discrimination Si/CsI(Tl) detection	*Pulse shape analysis*
Dimension [cm]	*50x50x85*
Power [W]	*30,0*
Mass [kg]	*37.3*

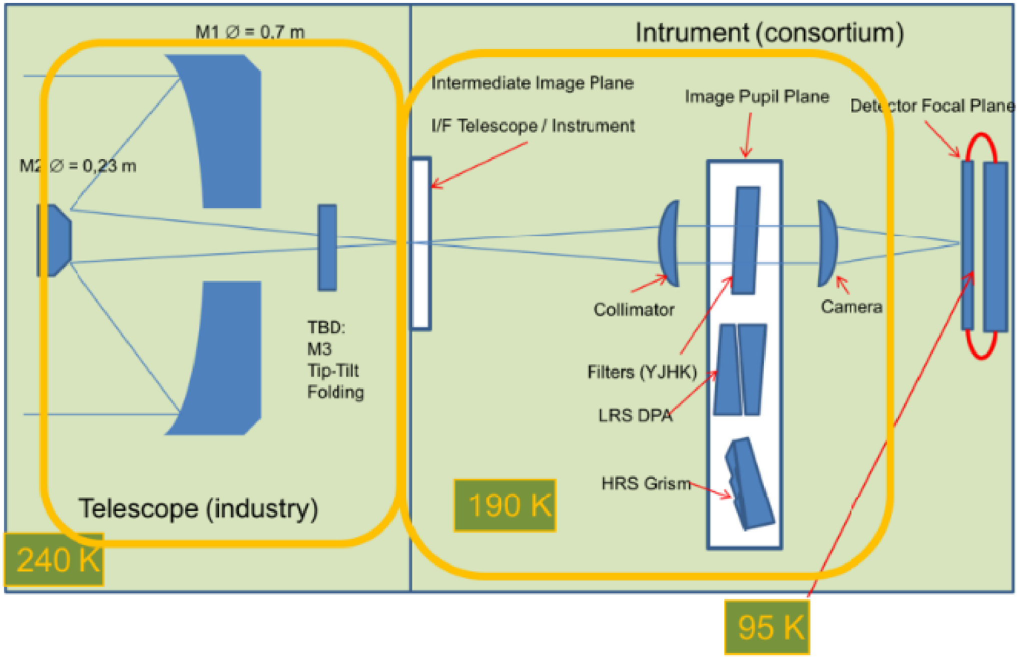


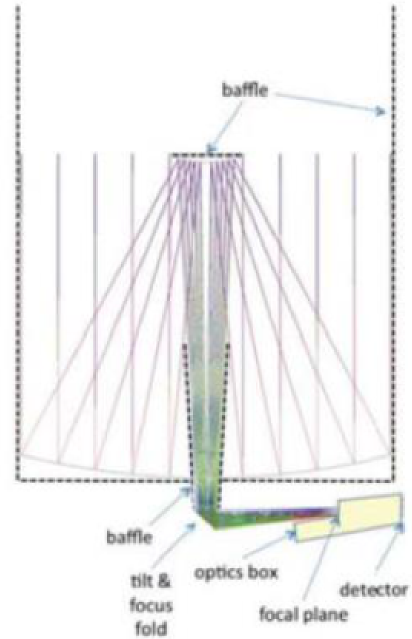




	2-30 keV	30-150 keV	>150 keV
Fully coded FOV	9 x 9 deg²		
Half sens. FOV	50 x 50 deg²	50 x 50 deg² (FWHM)	
Total FOV	64 x 64 deg²	85 x 85 deg² (FWZR)	2π sr
Ang. res	25 arcmin		
Source location accuracy	~5 arcmin (for >6 σ source)		
Energy res	200 eV FWHM @ 6 keV	18 % FWHM @ 60 keV	6 % FWHM @ 500 keV
Timing res.	1 μsec	1 μsec	1 μsec

The InfraRed Telescope (IRT)





Telescope type:	Cassegrain		
Primary & Secondary size:	700 mm & 230 mm		
Material:	SiC (for both optics and optical tube assembly)		
Detector type:	Teledyne Hawaii-2RG 2048 x 2048 pixels (18 µm each)		
Imaging plate scale	0".3/pixel		
Field of view:	10' x 10'	10' x 10'	5' x 5'
Resolution (λ/Δλ):	2-3 (imaging)	20 (low-res)	500 (high-res), goal 1000
Sensitivity (AB mag):	H = 20.6 (300s)	H = 18.5 (300s)	H = 17.5 (1800s)
Filters:	ZYJH	Prism	VPH grating
Wavelength range (µm):	0.7-1.8 (imaging)	0.7-1.8 (low-res)	0.7-1.8 (high-res, TBC)
Total envelope size (mm):	800 Ø x 1800		
Power (W):	115 (50 W for thermal control)		
Mass (kg):	112.6		

THESEUS mission profile

- Low-Earth Orbit (LEO), (< 5°, ~600 km)
- Rapid slewing bus (>10°/min)
- Prompt downlink (< 10-20s)
- Sky fraction that can be observed: 64%